

# NASA Langley Low Speed Aeroacoustic Wind Tunnel: Background Noise and Flow Survey Results Prior to FY05 Construction of Facilities Modifications

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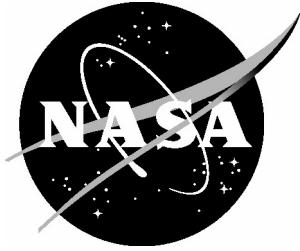
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*The NASA Langley Research Center Low Speed Aeroacoustic Wind Tunnel is a premier facility for model-scale testing of jet noise reduction concepts at realistic flow conditions. However, flow inside the open jet test section is less than optimum. A Construction of Facilities project, scheduled for FY 05, will replace the flow collector with a new design intended to reduce recirculation in the open jet test section. The reduction of recirculation will reduce background noise levels measured by a microphone array impinged by the recirculation flow and will improve flow characteristics in the open jet tunnel flow. In order to assess the degree to which this modification is successful, background noise levels and tunnel flow are documented, in order to establish a baseline, in this report.*

## **Introduction**

The NASA Langley Low Speed Aeroacoustic Wind Tunnel (LSAWT) is a low-speed, open-circuit, open jet acoustic wind tunnel equipped with a jet engine simulator (JES) for study of jet noise. LSAWT currently has a top speed of Mach 0.32. The jet engine simulator is equipped to produce two flow streams representing engine core and fan bypass flow. The jet flow streams are independently heated and throttled so that the engine cycle of nearly all existing and some proposed engines can be simulated. The jet flow is surrounded by the wind tunnel flow to simulate forward flight effects at realistic landing and takeoff speeds. The combined flow traverses an open jet test section surrounded by an anechoic chamber where microphones record noise produced by the simulated jet. As such, it is a valuable tool in the pursuit of jet noise suppression technology. A typical nozzle test is shown in figure 1.

As with all facilities, LSAWT can be improved. Three areas of improvement

currently planned for an FY05 Construction of Facilities (CoF) modification of the LSAWT are the addition of inlet noise suppression, installation of flow splitters to the existing downstream noise suppression baffles, and replacement of the existing flow collector. A sketch of the LSAWT tunnel circuit illustrating these potential areas of improvement is shown in figure 2. A study to assess circuit performance implications of the proposed modifications was reported in reference 1. Inside the test section, the open jet flow is captured by the collector. The existing collector is rather large for the room and may partially shield some of the microphones in the downstream side of the test section, so it would be desirable to have a physically smaller collector. In addition, the current collector is too large for the flow it is trying to capture. Flow spillage from the existing collector causes a complex recirculation pattern in the room that buffets acoustic treatment on the walls and ceiling and may affect background noise levels measured by the microphones. In addition, the size of the potential core flow of the open jet test section is reduced by reversed

flow spilling from the collector. The focus of the current study is to establish a baseline for assessment of the effects of installation of a new collector in the open jet test section by documenting the background noise levels and open jet test section potential core flow distribution and extent.

## **Symbols**

$c_0$	acoustic velocity, ft/s
$M$	Mach number, $v/c_0$
$p$	pressure, lb/ft <sup>2</sup>
$r$	distance from tunnel centerline, in
$q$	dynamic pressure, lb/ft <sup>2</sup>
SPL	sound pressure level, dB
$t$	Rankin temperature, degree
$u$	velocity in streamwise direction, ft/s
$v$	velocity, ft/s
$x$	axial distance along tunnel centerline, referenced from contraction exit, positive in flow direction, in
$y$	lateral distance from tunnel centerline, in
$z$	vertical distance from tunnel centerline, positive up, in
$\rho$	density, slug/ft <sup>3</sup>

### **Subscripts**

$s$	static
$sc$	scaled
$t$	total

## **Test Description**

### **Microphone Array**

Background noise measurements were conducted using the standard LSAWT microphone array consisting of 28 B&K model 4939 quarter-inch diameter free-field response microphones. The microphone locations with respect to the centerline of the contraction exit are shown in table 1. Data were acquired at a sample rate of 210 kHz, with the data high-pass filtered at 200 Hz and anti-alias filtered at 100 kHz. The data were then processed into spectra with

bandwidth of 30.52 Hz up to a maximum frequency of 100 kHz. The SPL values presented represent sound pressure levels relative to the constant bandwidth and were not normalized to power spectral density levels. Data were acquired at the following test section Mach numbers: 0.10, 0.16, 0.20, 0.24, and 0.28.

Table 1. Location of Microphones.

No.	x, in	y, in	z, in	r, in
1	-76.06	88.39	106.62	138.50
2	-53.78	88.39	106.62	138.50
3	-34.54	88.39	106.62	138.50
4	-17.52	88.39	106.62	138.50
5	-2.14	88.39	106.62	138.50
6	12.03	88.39	106.62	138.50
7	25.33	88.39	106.62	138.50
8	38.02	88.39	106.62	138.50
9	50.32	88.39	106.62	138.50
10	62.44	88.39	106.62	138.50
11	74.56	88.39	106.62	138.50
12	86.860	88.39	106.62	138.50
13	99.550	88.39	106.62	138.50
14	112.85	88.39	106.62	138.50
15	127.02	88.39	106.62	138.50
16	142.40	88.39	106.62	138.50
17	150.67	88.39	106.62	138.50
18	159.42	88.39	106.62	138.50
19	168.71	88.39	106.62	138.50
20	178.66	88.39	106.62	138.50
21	189.35	88.39	106.62	138.50
22	200.94	88.39	106.62	138.50
23	213.59	88.39	106.62	138.50
24	227.50	88.39	106.62	138.50
25	242.94	88.39	106.62	138.50
26	260.24	88.39	106.62	138.50
27	279.84	88.39	106.62	138.50
28	302.33	88.39	106.62	138.50

### **Data Analysis of Acoustic Measurements**

As shown in references 2 and 3, background noise data from low speed open-jet wind tunnels can be scaled to a common Mach number using a two part scaling law based

on a  $u^4$  scaling law. First, the frequency of each spectral bin is scaled to a new frequency using a Strouhal scaling law.

$$f_{sc} = f (u_{sc} / u)$$

Then the amplitude of sound pressure level is scaled using the relation

$$SPL_{sc} = SPL + 40 \log_{10}(u_{sc} / u)$$

Resulting scaled spectra should collapse to spectra obtained at the scaled Mach number for wind tunnel background noise. Excessive background noise levels due to impingement of recirculation flow on the microphones will not scale using this method, so the affected microphones and test conditions can be isolated using this scaling method.

### Flow Survey Rake

The wind tunnel flow was surveyed upstream of the collector to document spatial extent and flow distribution in the open jet potential core flow. The total pressure distribution in the lower half of the test section open jet flow was surveyed in a single plane 1 ft upstream of the current collector using the total pressure rake shown in figure 3. Data were obtained in four sections, which, when combined covered an area 11.67 ft wide by 5 ft tall. Total pressure probes were spaced at 1.0 inch intervals along the pressure rake. Data were obtained in 3.0 inch spacing intervals. As a result the data grid spacing is 1.0 inch vertically and 3.0 inches laterally.

### Data Analysis of Flow Survey Data

Test chamber static pressure was used to reduce the total pressure data to differential pressure data. The differential pressure data were further used to compute velocity distribution by Bernoulli's equation .

$$q = p_t - p_s = \frac{1}{2} \rho u^2$$

The differential pressure and velocity data were normalized by nominal dynamic pressure and velocity values for the tunnel Mach number test conditions. The values used are presented in table 2.

Table 2. Nominal pressure and velocity data.

M	q, psf	u, ft/s
0.20	59.2	223.28
0.28	116.1	312.59

## Results

### Acoustic Results

Narrowband background noise data measured as a function of wind tunnel Mach number for each microphone is presented in figure 4. In figure 4.a., the amplitude of test chamber background noise is shown to increase with increasing Mach number, which is exactly what is expected.

It has been observed, both at model scale (reference 1) and in full-scale operation, that the test section recirculation flow is caused by flow spillage from the current collector. The current collector is too large for the open jet flow, and, as a result, the boundary of the open jet potential core flow impinges well inside the collector. Flow outside of the flow boundary then reverses direction and exits from the front of the collector. This reversed flow not only reduces the size of the open jet potential core, but sets up a complex recirculation flow in the test chamber. In order to sort out the influence of test chamber recirculation impingement on background noise data, the data were scaled to a Mach number of 0.15. The resulting scaled data is presented in figure 5. As shown for microphone 1 in figure 5.a., the scaling resulted in a very good collapse of the data to a common scaled sound pressure level as a function of frequency curve. This indicates that the data measured at microphone 1 is primarily acoustic and was minimally affected by effects such as test chamber recirculation. Figures 5.b – bb.

also show that the data, in general, scales well for the other microphones with some notable exceptions. It should also be noted that the data presented in figure 5 does not scale as well at very low frequencies, since the data were high pass filtered at 200 Hz, nor at very high frequencies as the data were anti-alias low pass filtered at 100 kHz.

Some of the data in figure 5 does not scale as well as other data, and that is precisely the effect sought by scaling the data. One example is the relatively broadband signal difference between the Mach 0.10 scaled data and the remainder of the scaled data, such as that shown in data from microphones 13-20 (figures 5.m. through 5.t.). This low frequency broadband effect may be due to recirculation in the test chamber and the impingement of the recirculation flow on the microphones in this range dominates the test chamber background noise at  $M = 0.10$ . Comparison with the corresponding unscaled data shown in figures 4.m. to 4.t. suggest that the frequency range that is most affected is between 200 Hz and 500 Hz. This set of data was high pass filtered at 200 Hz, so this result suggests that data obtained at lower frequencies may also be affected. Scaled data from figure 5 suggests that the broadband spectral feature may increase sound pressure levels as much as 20 dB over scaled acoustic data levels. A reduction in test chamber recirculation would likely lower the influence of recirculation on measured acoustic levels significantly in the low frequency range at low Mach numbers. For data obtained at higher Mach numbers, it appears that the acoustic background noise dominates the impingement flow effect, so any measured background noise level improvement will likely be less than for lower Mach number cases.

For completeness, the background noise data set is presented as one-third octave band data in figure 6. Effects noted in the

discussion of figure 5 are evident, but not as pronounced as in figures 4 and 5 using narrowband data.

There were also a few notable anomalies in the data. The trend of SPL increasing with increasing Mach number is shown in most of the data presented in figure 4, but data shown for microphone 22 in figure 4.v. show that this trend is less than for other microphones. In figure 5.v., the data from microphone 22 is shown not to scale well. The shape of the spectral curve shown in figures 5.v. and 4.v. are indicative of a saturated data channel. Typically data from a saturated channel, when plotted as shown in figure 4, will resemble a straight line. The saturation of this data channel could result from a defective microphone that may have been damaged by, among other things, impingement of recirculation flow.

Data obtained for microphone 2 in figure 5.b. shows evidence of a tone-like feature at about 800 Hz (scaled frequency) that did not scale with Mach number. Comparing this result with figure 4.b. shows that the tone, shown to exist at 500 Hz at Mach 0.10, appears to be present in the data for all Mach numbers, but that the level at Mach numbers greater than 0.10, the tone is masked by the generally rising sound pressure level. The source of this tone is probably not driven by test section velocity, since the amplitude is about the same at all Mach numbers, and the frequency did not scale with Mach number, both of which would be expected for a flow-driven tone. This could be a mechanical noise in the test chamber. Interestingly, the tone did not manifest itself in data obtained with microphones 3 and 4 (figures 5.c. and 5.d., respectively), however, a similar tone is shown in microphone 5 data (figure 5.e.). The fact that the tone was not measured by adjacent microphones suggests that the tone was not acoustic in nature and may indicate an electrically induced signal contamination



at some point in the data acquisition system. A similar feature is also evident in data from microphone 13 (figure 5.m.) and is not evident in the remainder of the microphone signals.

It is anticipated that possible improvement in test chamber flow due to the new collector design should improve test section recirculation effects. The degree to which that improvement is realized will be most evident in the low frequency data at low Mach number tunnel operation for a set of microphones that include microphones 13-23.

### **Flow Survey Results**

Test section flow was surveyed over the lower half of the open jet flow in a plane 1 ft upstream of the collector. Data were obtained for two Mach numbers with no JES flow, and one case where the JES flow was operated at a flow condition typical of jet nozzle research test conditions.

The purpose of the current measurement is to document existing flow distribution. Only data where positive values for total pressure were obtained are presented. Negative values for total pressure can result from flow measurement in areas of high flow turning, or even reversed flow. However, the flow probes are not calibrated to accurately measure flow in either of those cases, so those data were not plotted. Reversed flow due to flow spillage from the collector would be expected to reduce the spatial extent of the open jet potential core flow, and perhaps reduce the uniformity of that flow. The intent is to document the spatial extent and uniformity of the potential core flow, so that any improvement due to the new collector design will be evident in calibration tests performed after the CoF.

In figure 7, for a wind tunnel condition of  $M = 0.20$ , the distribution of dynamic pressure, normalized by a nominal value for dynamic

pressure, over the survey plane is presented in part a., while the velocity distribution derived from that pressure distribution, normalized by a nominal value for velocity, is presented in part b. In part a., it is also interesting to note that the potential core flow of the open jet is not uniform, as would be nearer the case in a typical wind tunnel flow. This result is unique to LSAWT because the JES is mounted in the test section flow. The presence of the JES and the JES support strut in the core flow causes a flow deficit. Although the JES is centered in the tunnel flow, it is interesting to note that the flow deficit inside the 80 percent dynamic pressure contour appears in the lower half of the test section flow, which indicates that the presence of the JES in the flow turns the flow downward, as may be expected. The flow deficit from the JES also appears in the normalized velocity distribution in part b., the flow deficit is not as readily obvious. In addition, the lower boundary of the tunnel flow data shows less flow in the center of the test section, and this flow feature is likely caused by the JES support strut wake.

The leading edge of both the existing and new collectors are plotted on the figure for comparison with the open jet flow survey. It is apparent that for  $M = 0.20$ , the leading edge of the existing collector covers a much larger area than the open jet flow, and that the leading edge of the new collector is much closer in area to the open jet flow. Hopefully, this is an indication that the new collector will better match the open jet flow and result in less test chamber recirculation flow.

In figure 8, flow survey for the  $M = 0.28$  test condition is presented. Comparison with figure 7 leads to the impression that the open jet core flow is very similar in distribution with the  $M = 0.20$  case. Once again, the capture area of the new collector is much closer to the spatial extent of the open jet

potential core flow than the existing collector.

Figure 9 shows a flow condition where the wind tunnel flow is set to  $M = 0.28$ , and the JES flow is set to a representative “cold” take-off condition, with nozzle pressure ratios set to 1.75 and 1.56 in the fan and core streams, respectively. Total pressure in the exhaust of the JES exceeded the range of the pressure transducers used for the flow survey, so the JES plume was not measured. It is noteworthy that the shape and distribution of the open jet flow is not greatly affected in areas outside of the area of the JES plume flow.

The statement that the flow profiles look similar is supported by plotting the normalized velocity profile across a section close to the test section centerline for the three flow conditions presented in figures 7-9. The open jet test section flow is shown to be very similar for the three flow conditions for the ranges  $-4.0 \text{ ft} < y < -1.2 \text{ ft}$  and  $1.2 \text{ ft} < y < 4.0$ . The range  $-1.2 \text{ ft} < y < 1.2 \text{ ft}$  is very similar for the two cases where the JES was turned off, and is significantly different for the JES flow on case, as would be expected. This result is significant in that it confirms that the shape of the open jet flow is relatively independent of tunnel Mach number, and further, is not greatly affected by JES operation.

### **Conclusions**

Background noise levels and open jet flow distribution were surveyed in the Low Speed Aeroacoustic Wind Tunnel prior to FY05 Construction of Facilities modifications in order to provide a baseline data set of existing test section conditions. This baseline data set can be used to assess improvements in test chamber background noise levels and open jet flow resulting from installation of a new collector in the test chamber.

Background noise data, when scaled to a common test section flow velocity, suggest that, for a range of microphones, a low frequency relatively broadband portion of the background noise may well be due to test section recirculation flow. The amplitude of this spectral feature may be as much as 20 dB greater than scaled acoustic data levels for the lowest speed case surveyed,  $M = 0.10$ . Acoustic data obtained with microphone 22 was determined to be saturated probably due to failure of the microphone. Another spectral feature, a tone-like feature, seemed to be present in data from several non-adjacent microphones, which suggests an electronic, contamination to the background data set for those channels.

Flow survey data conducted over the lower half of the open jet test section flow in a plane upstream of the existing collector clearly shows the flow deficit caused by the presence of the JES in the wind tunnel flow. The flow distribution was shown to be independent of wind tunnel Mach number and, outside of a region dominated by JES exhaust, independent of JES operation.

### **References**

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2. Ahuja, K. K.; Stoker, R.; Massey, K.; “In-Flow and Nearfield Out-of-Flow Noise in Open-Jet Wind Tunnels”, NWTC Project Archive, September 1995.
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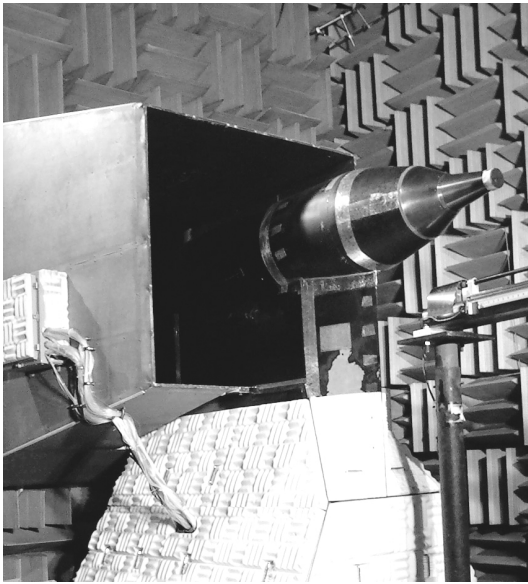


Figure 1. Typical LSAWT test setup.

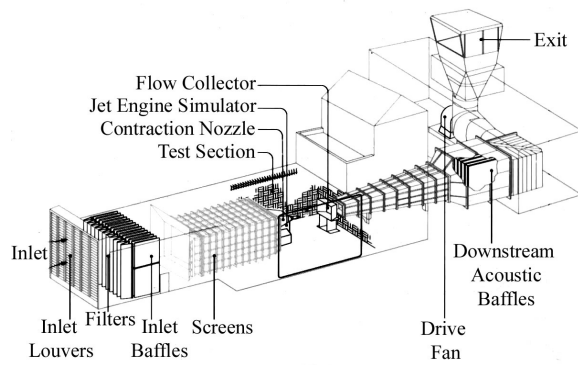
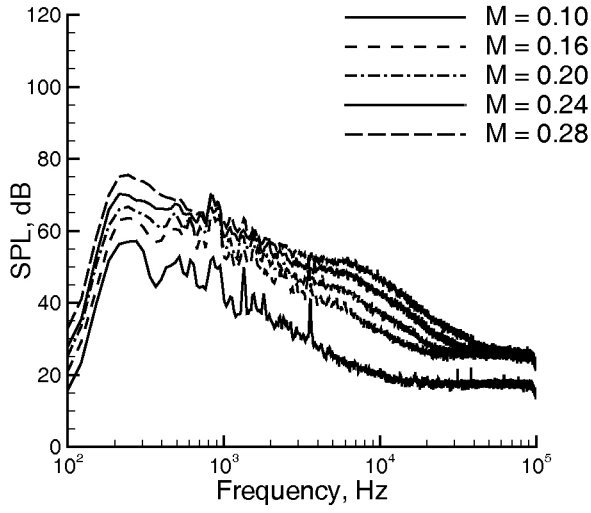


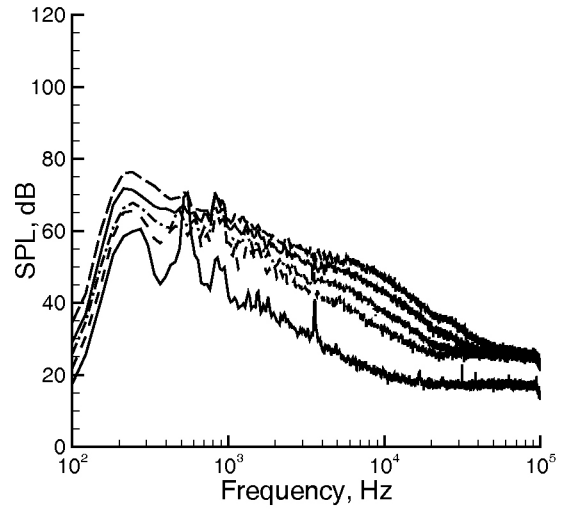
Figure 2. Sketch of LSAWT circuit.



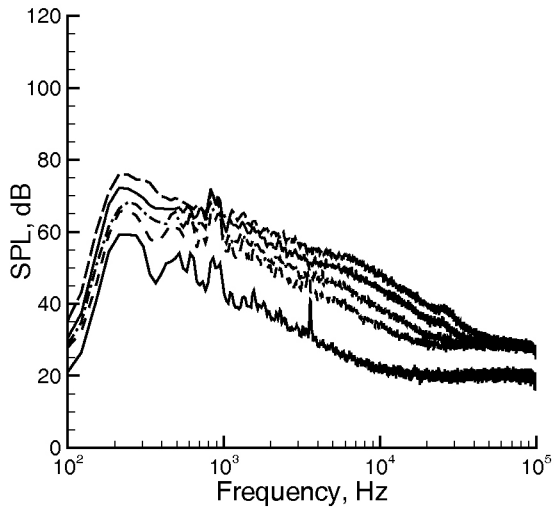
Figure 3. Flow survey rake installed in LSAWT test section.



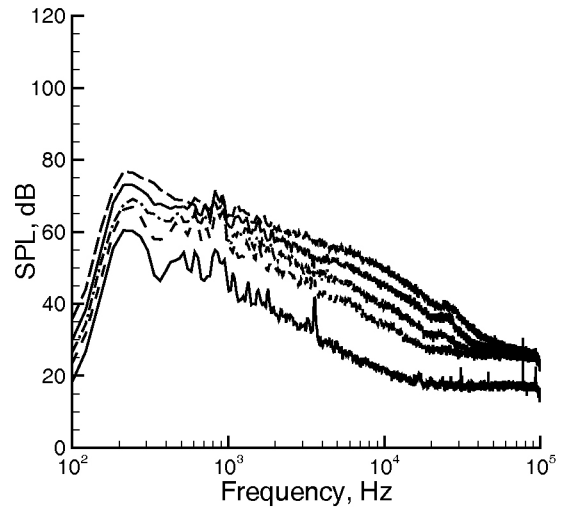
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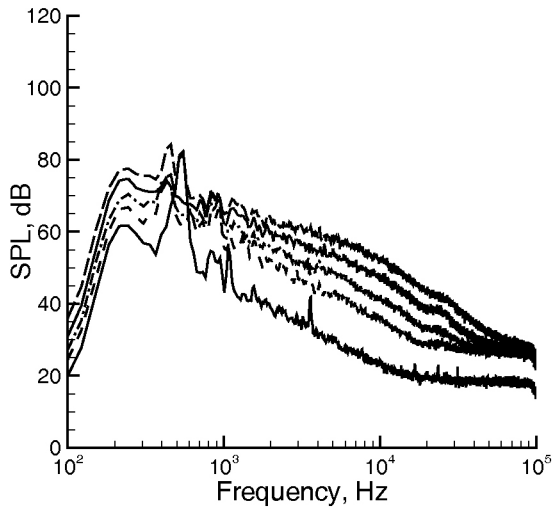
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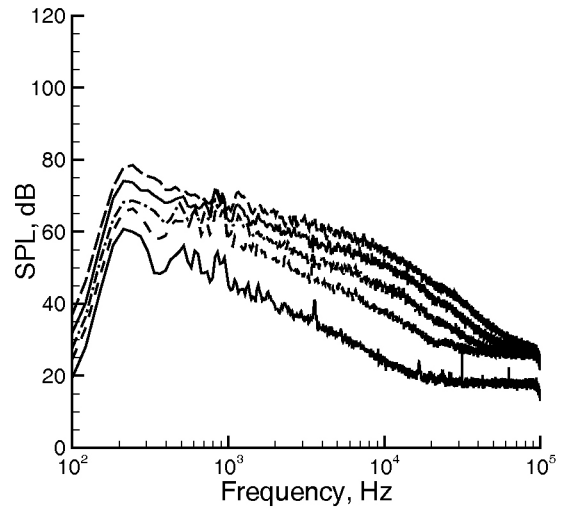
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d. Microphone 4

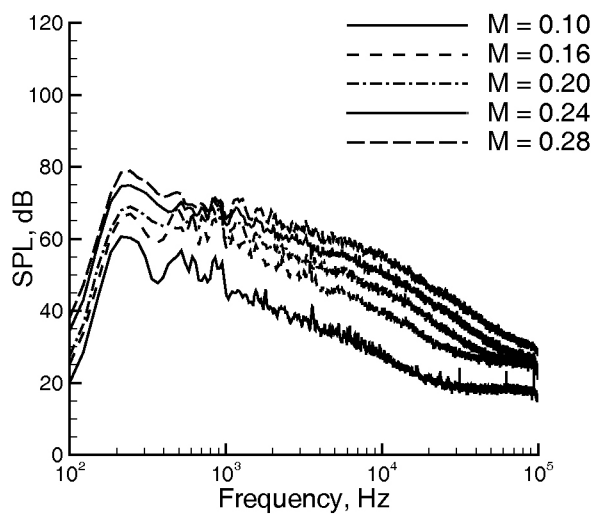


e. Microphone 5

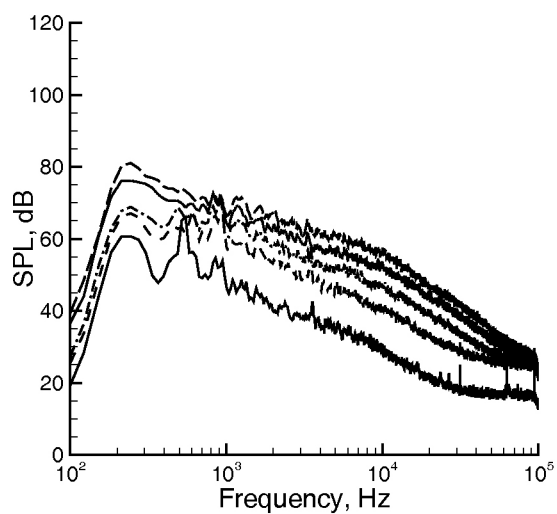


f. Microphone 6

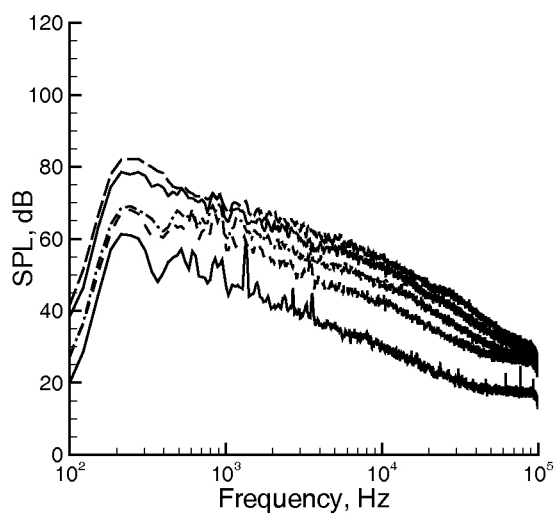
Figure 4. Narrowband acoustic data as a function of Mach number for each microphone.



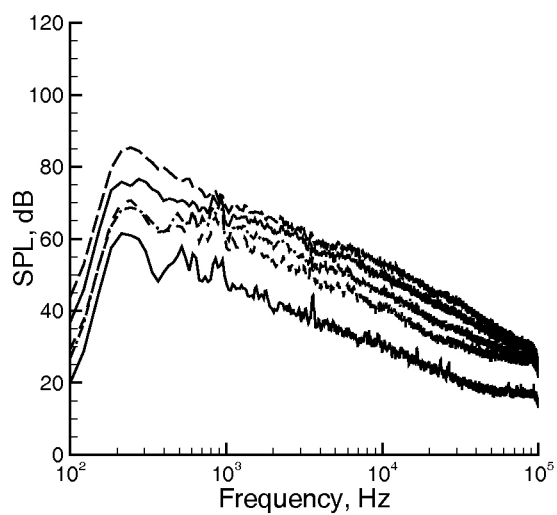
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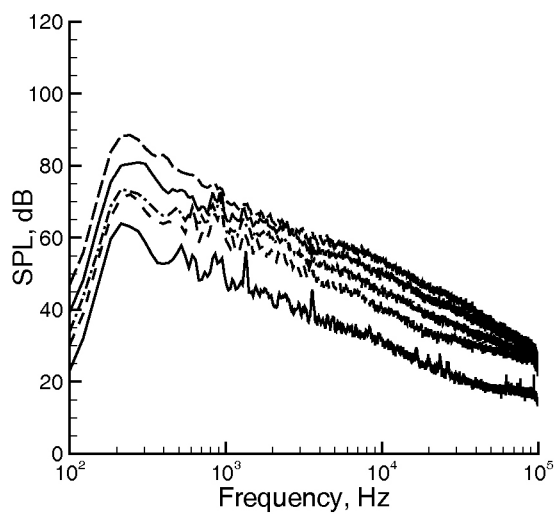
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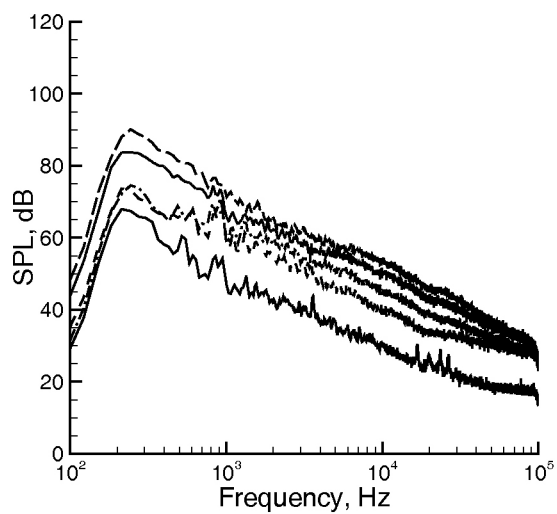
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j. Microphone 10

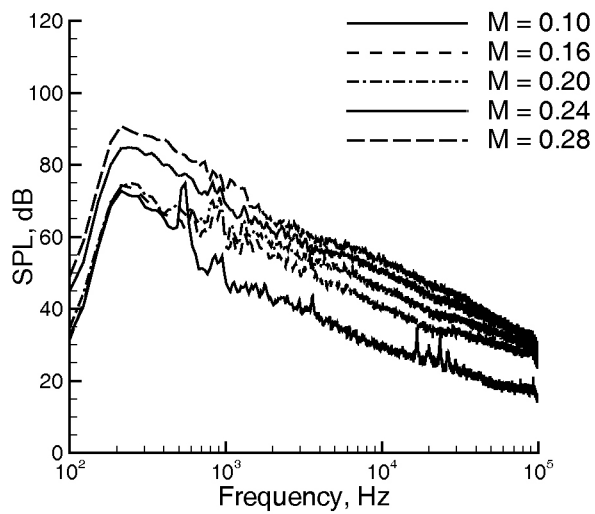


k. Microphone 11

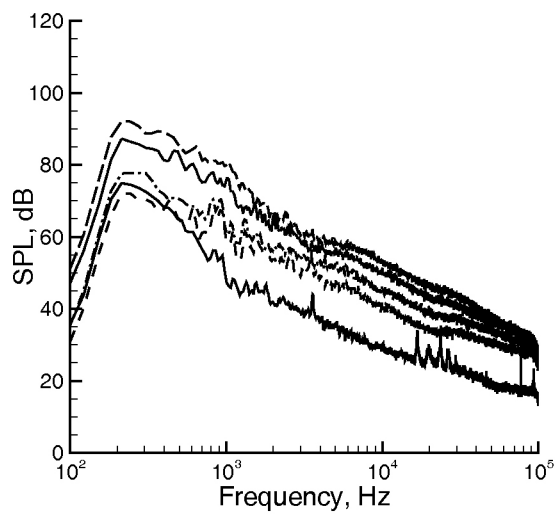


l. Microphone 12

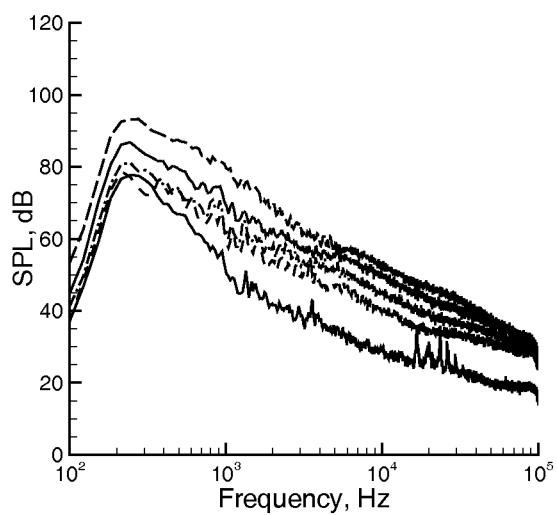
Figure 4. Continued.



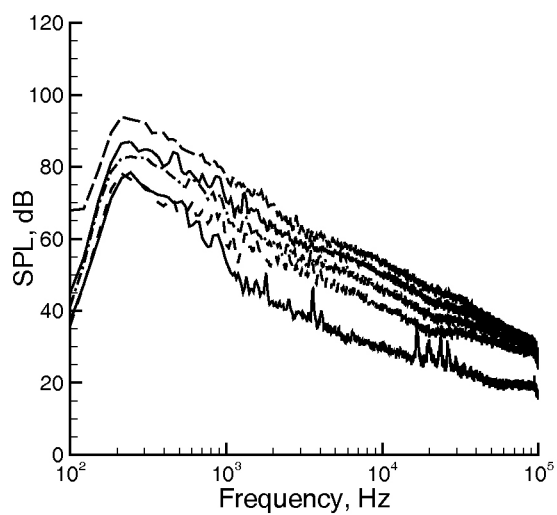
m. Microphone 13



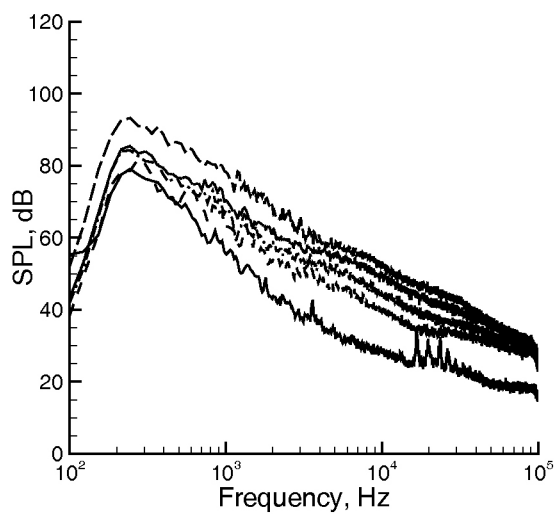
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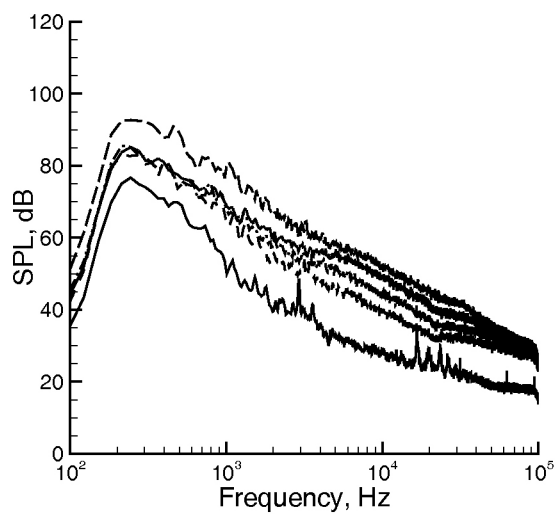
o. Microphone 15



p. Microphone 16

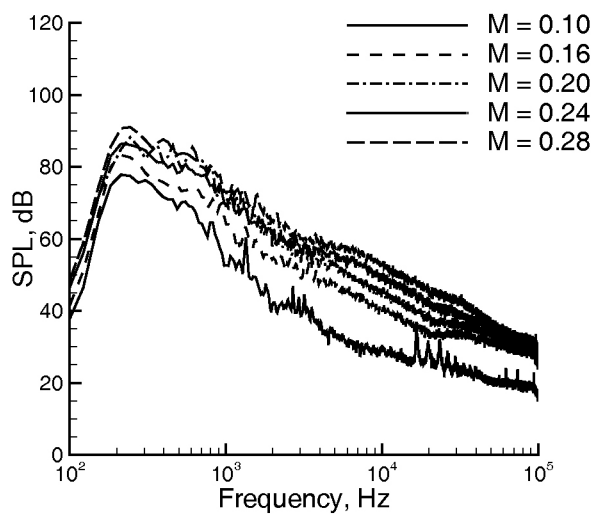


q. Microphone 17

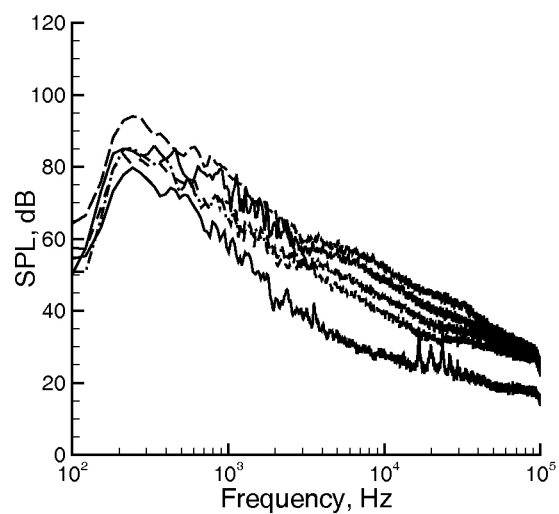


r. Microphone 18

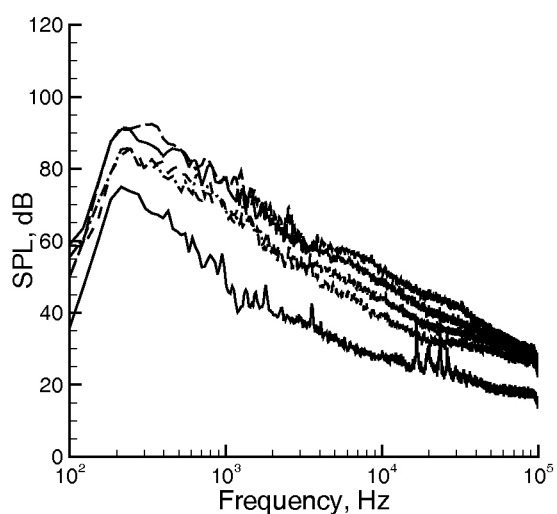
Figure 4. Continued.



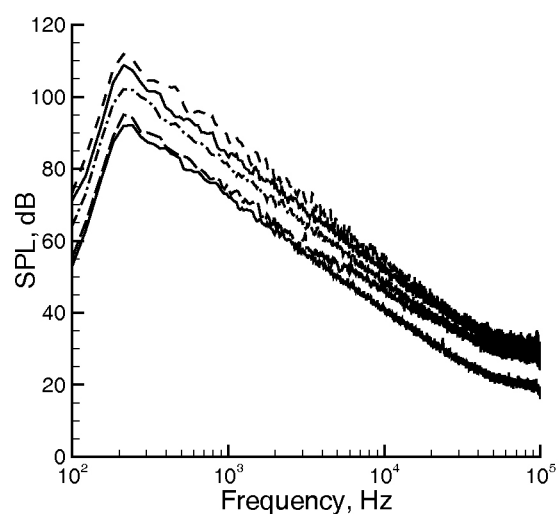
s. Microphone 19



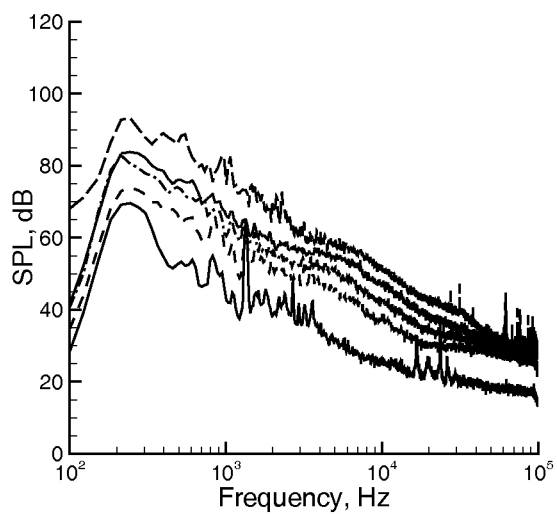
t. Microphone 20



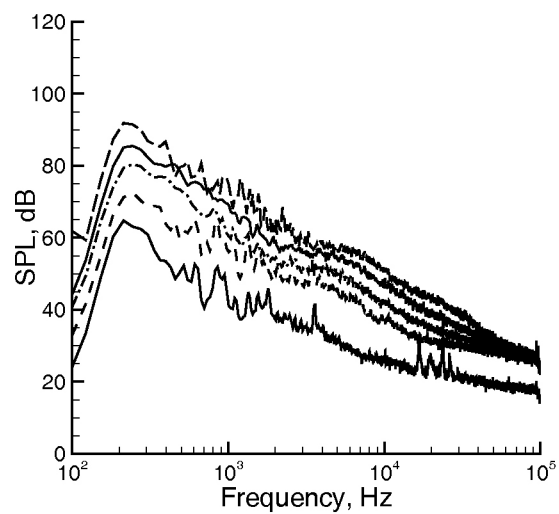
u. Microphone 21



v. Microphone 22



w. Microphone 23



x. Microphone 24

Figure 4. Continued.

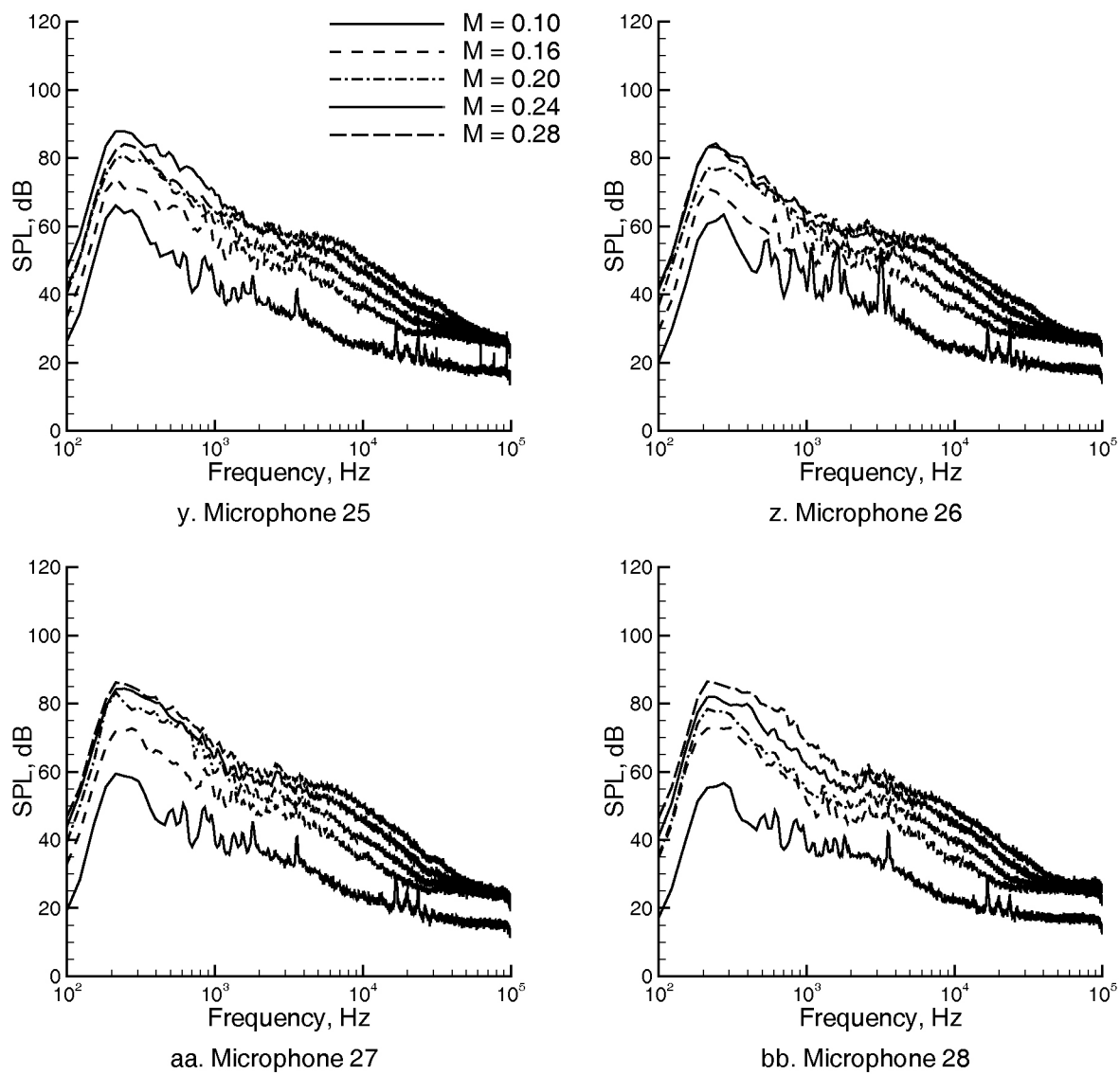
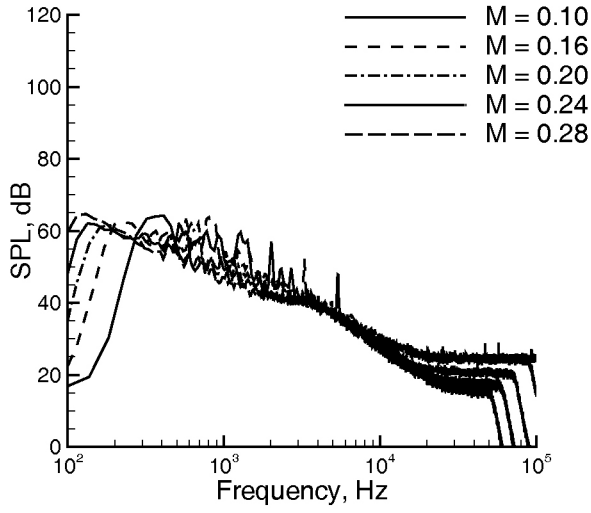
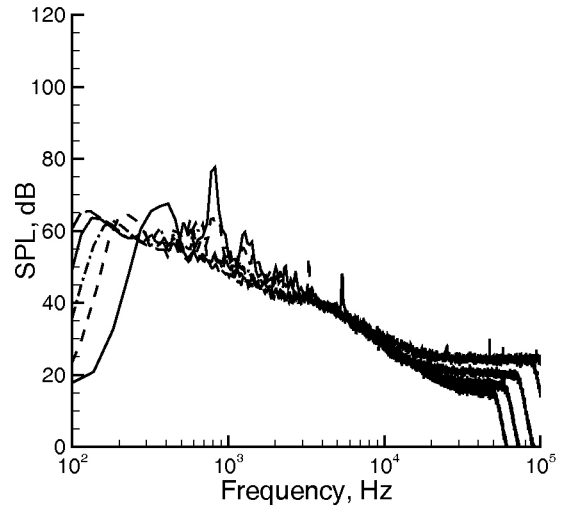


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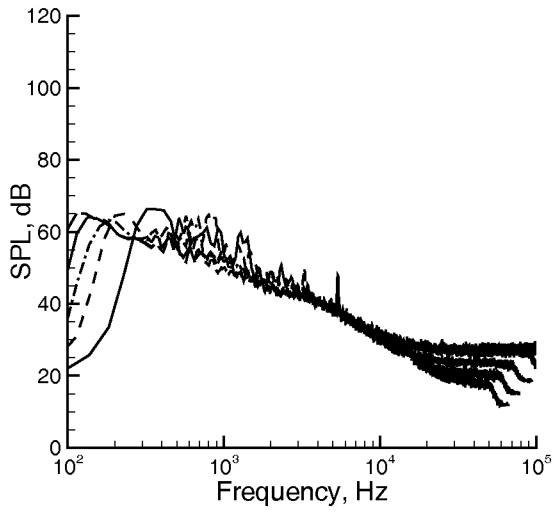




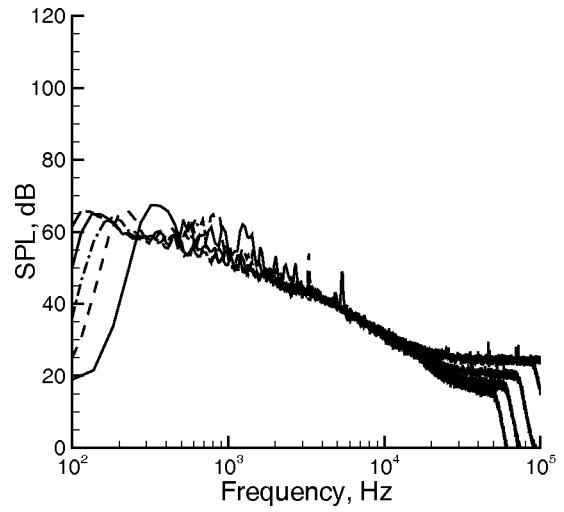
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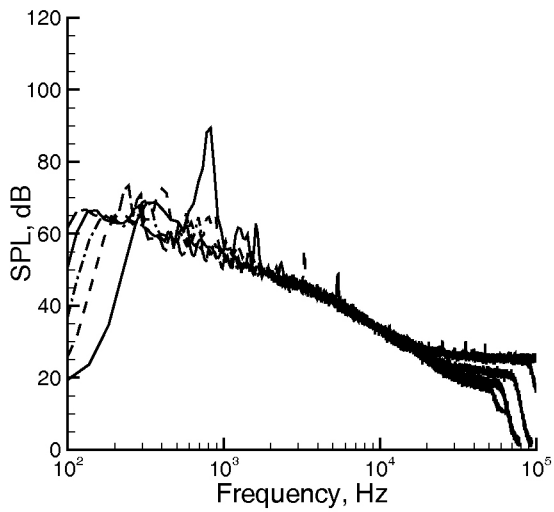
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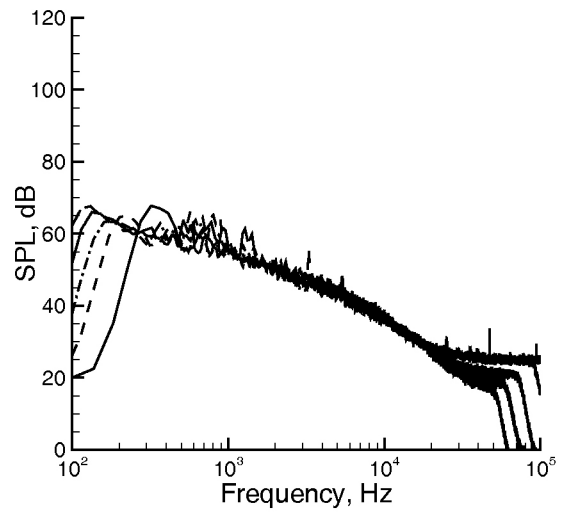
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d. Microphone 4

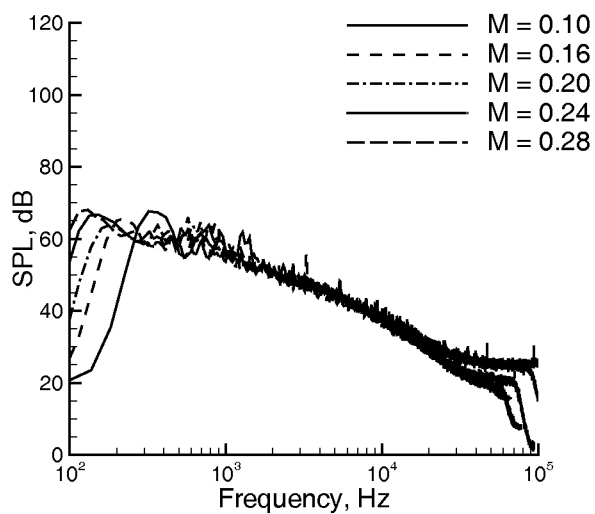


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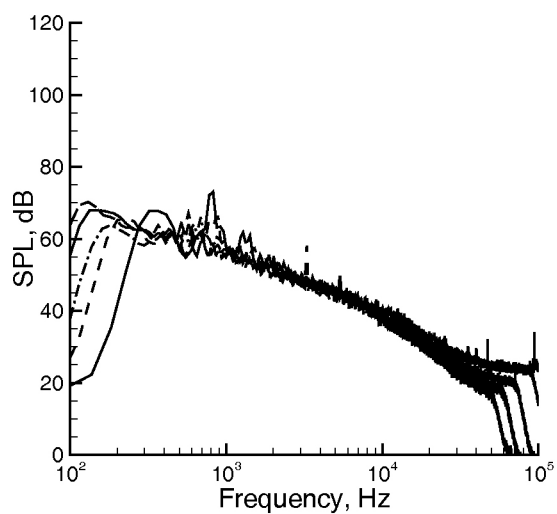


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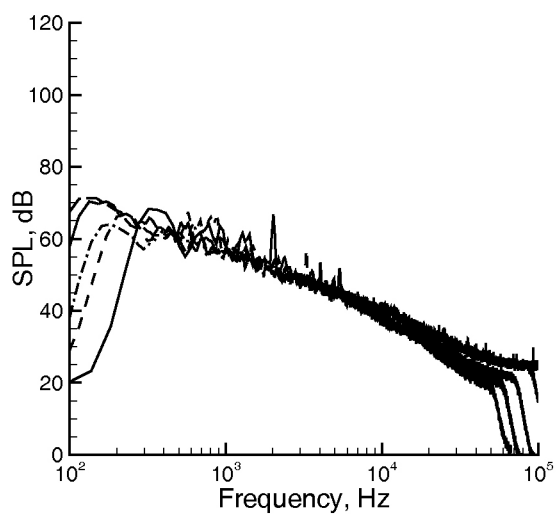
Figure 5. Acoustic data scaled to Mach = 0.15 using a  $u^4$  scaling method.



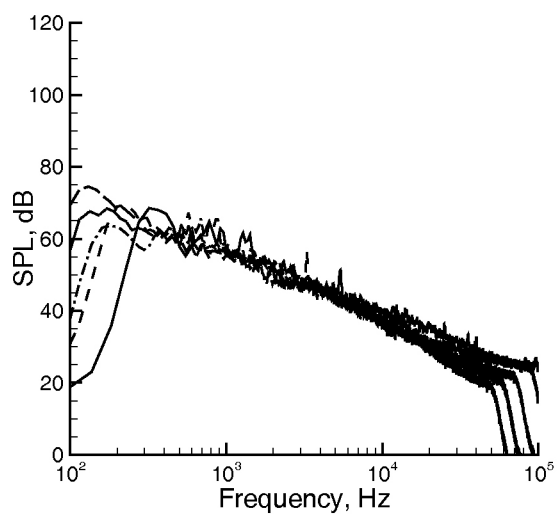
g. Microphone 7



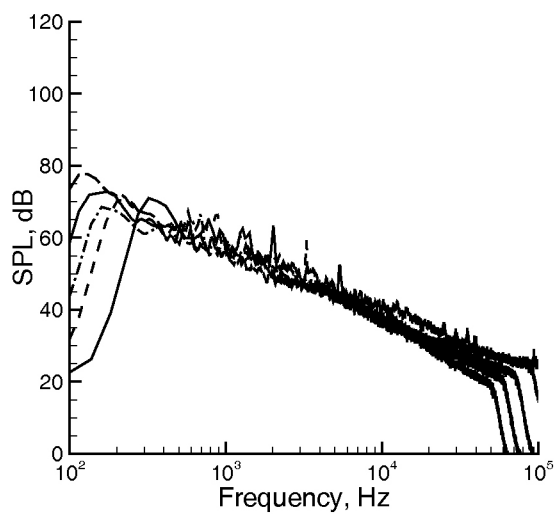
h. Microphone 8



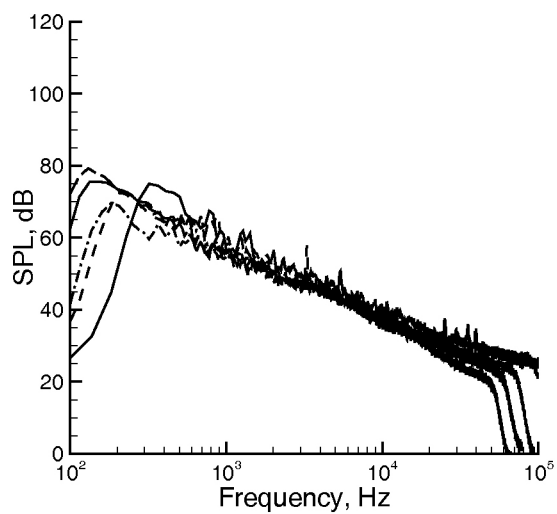
i. Microphone 9



j. Microphone 10

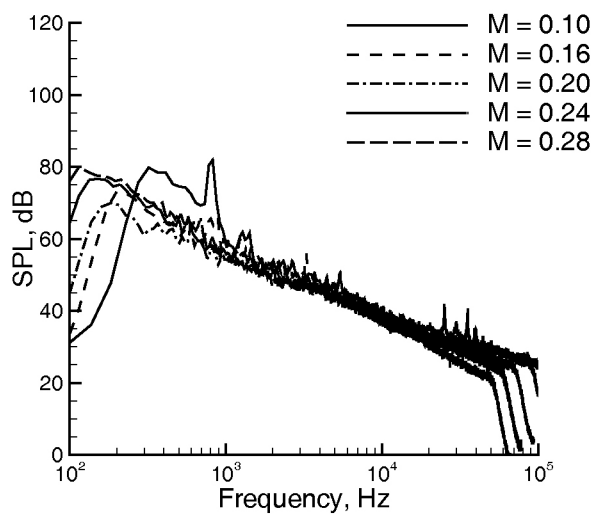


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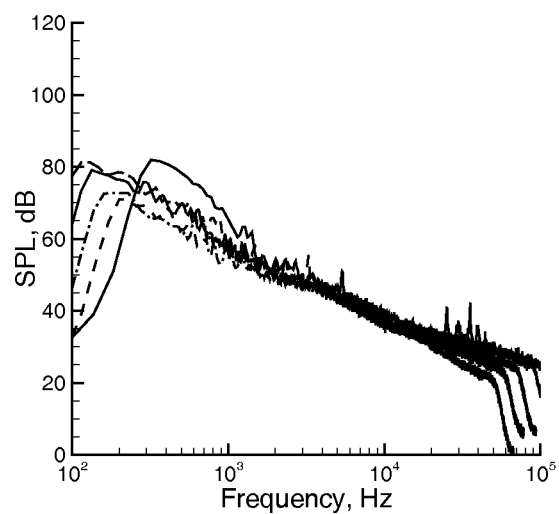


l. Microphone 12

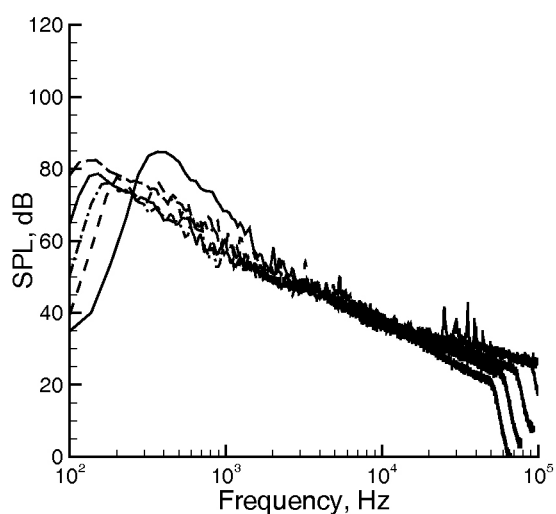
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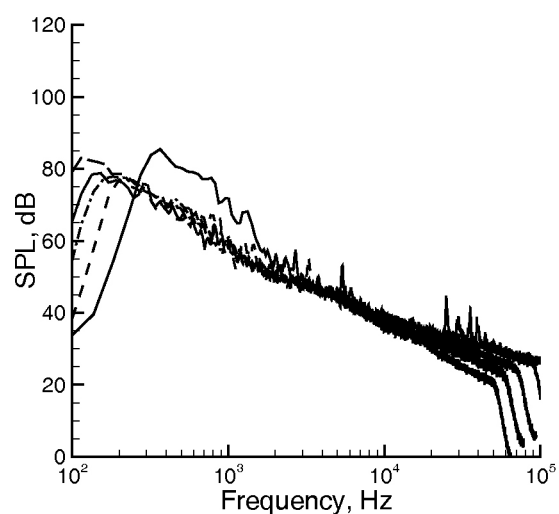
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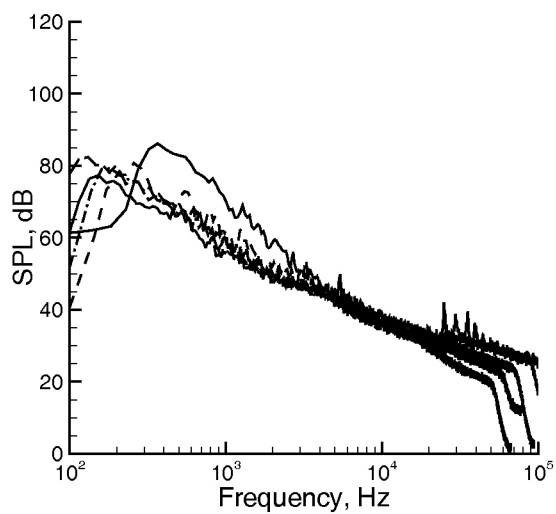
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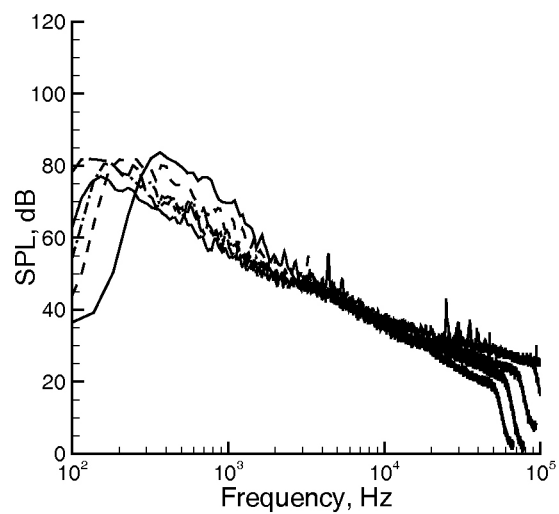
o. Microphone 15



p. Microphone 16

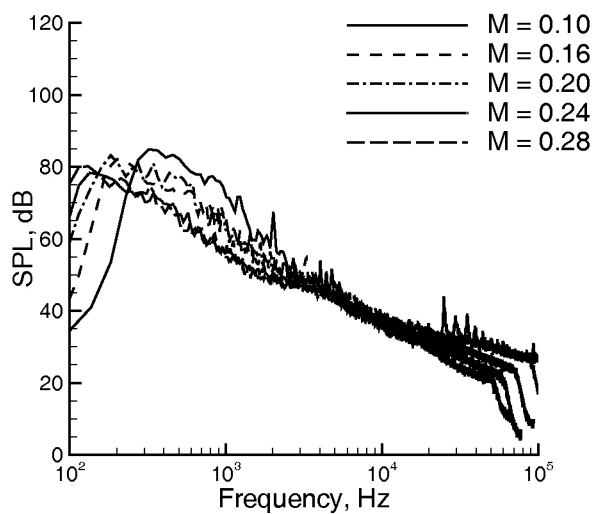


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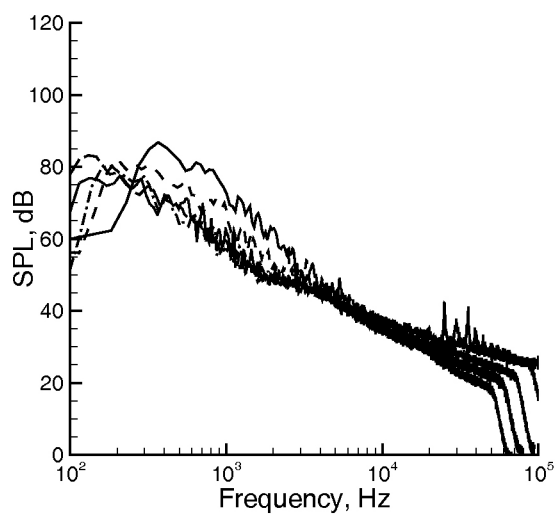


r. Microphone 18

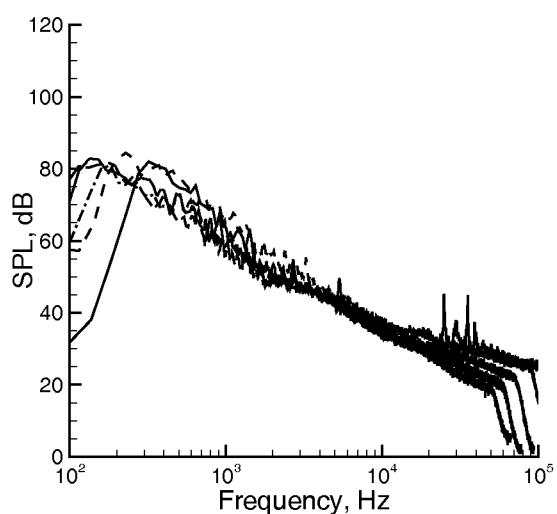
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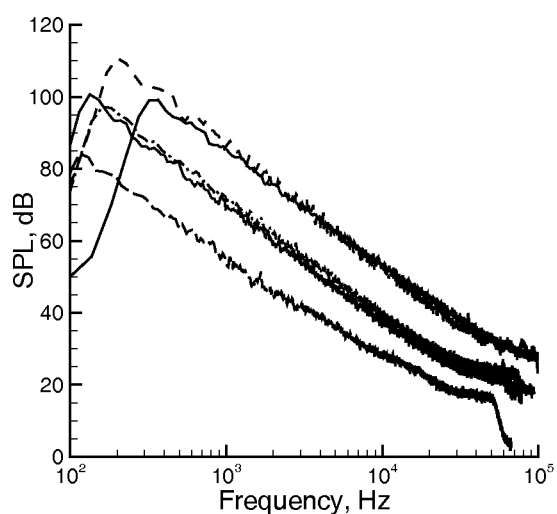
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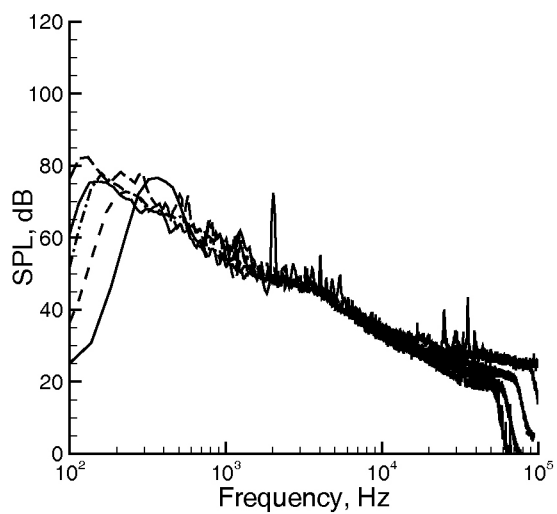
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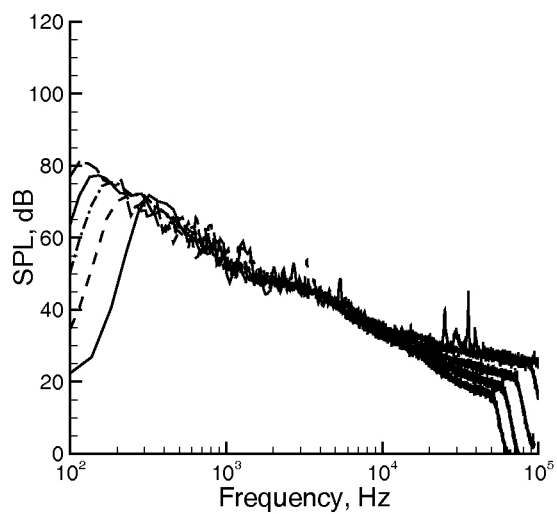
u. Microphone 21



v. Microphone 22



w. Microphone 23



x. Microphone 24

Figure 5. Continued.

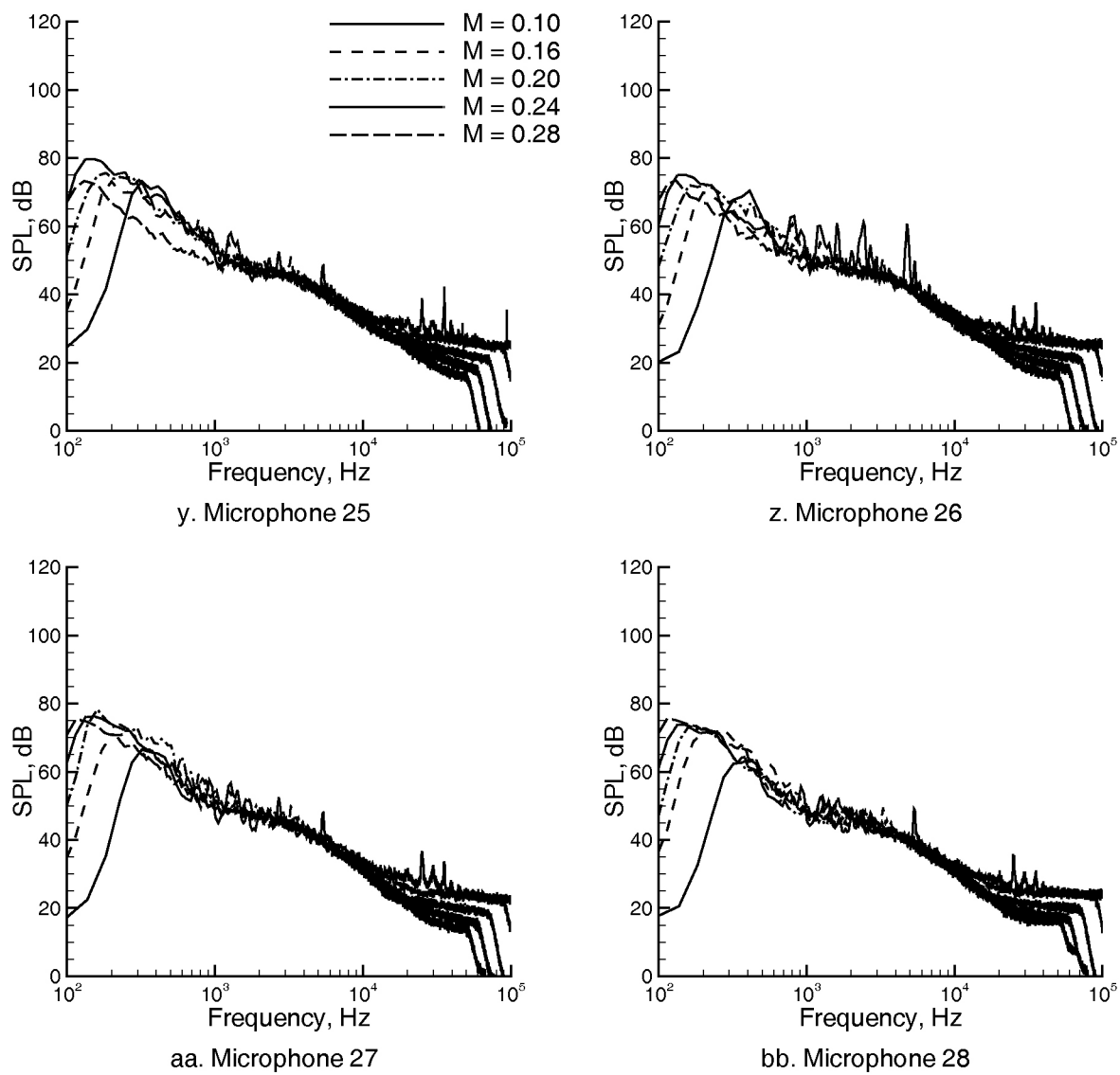


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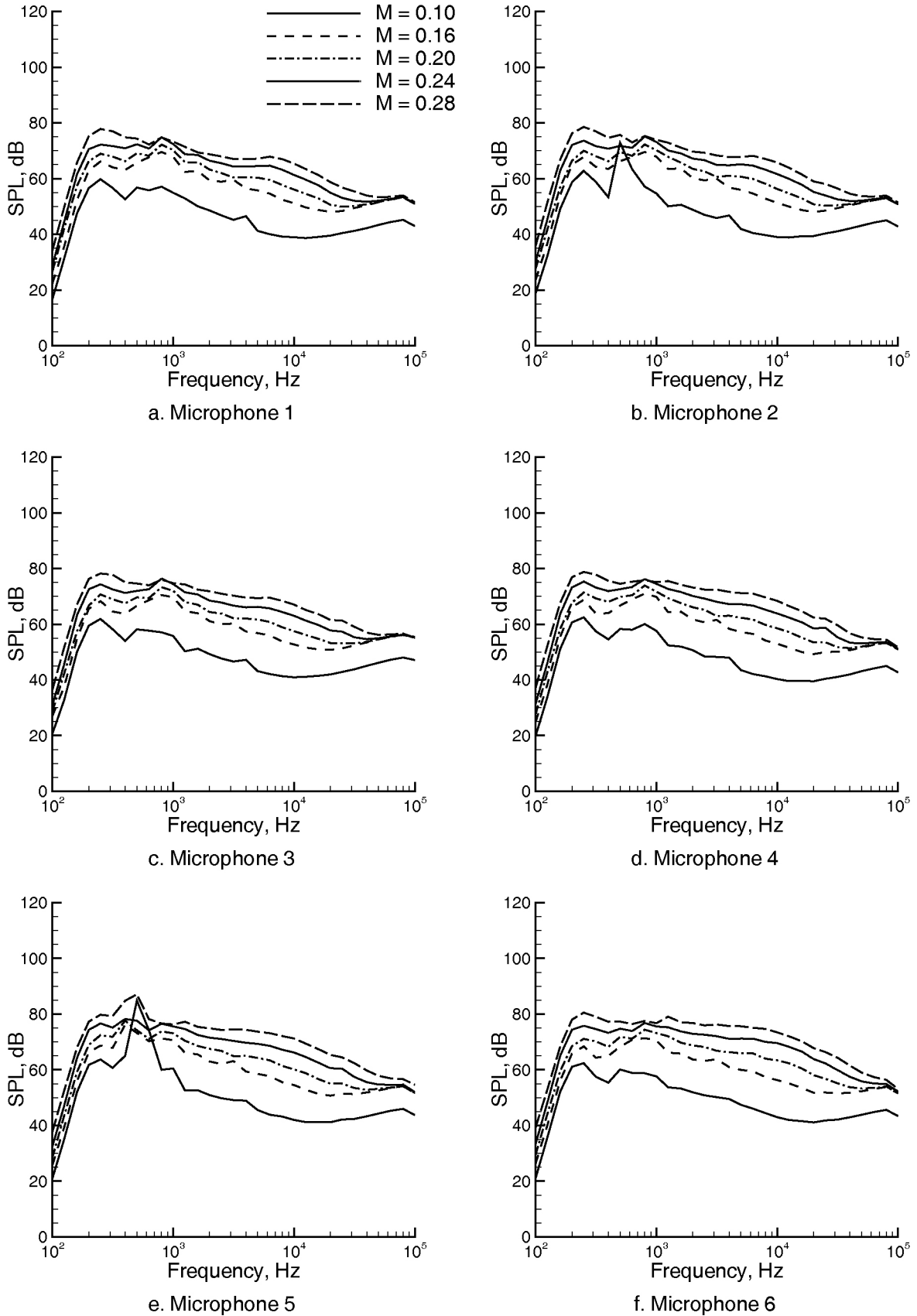
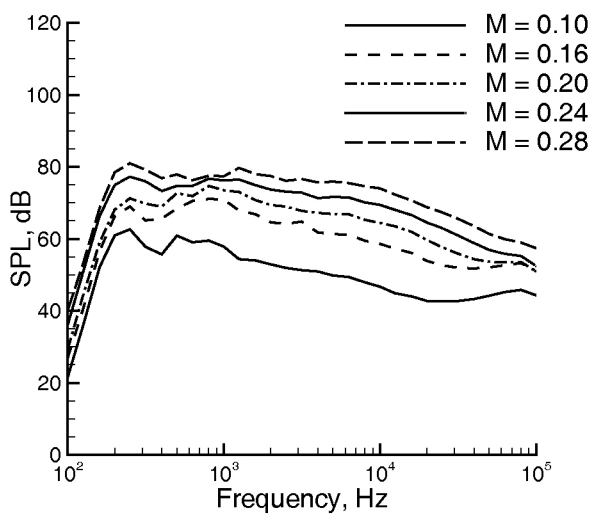
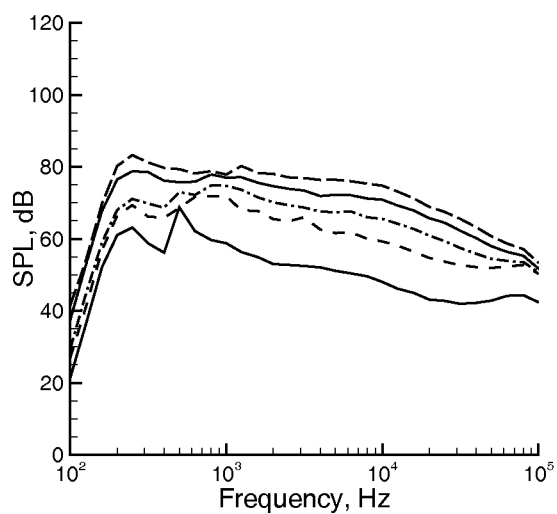


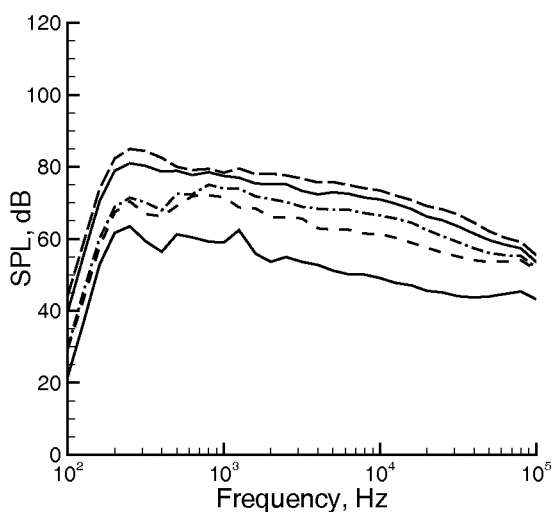
Figure 6. 1/3 Octave band acoustic data as a function of Mach number for each microphone.



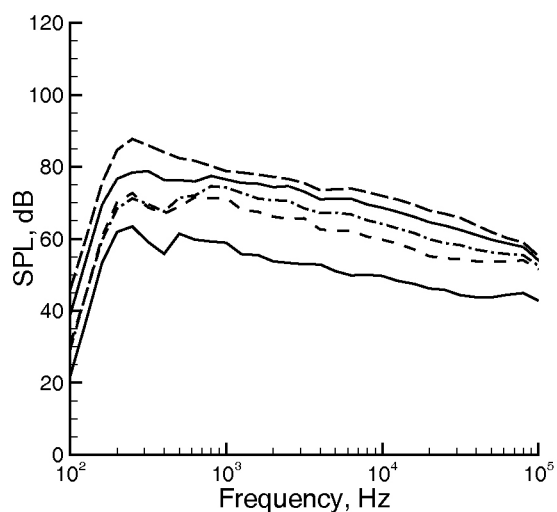
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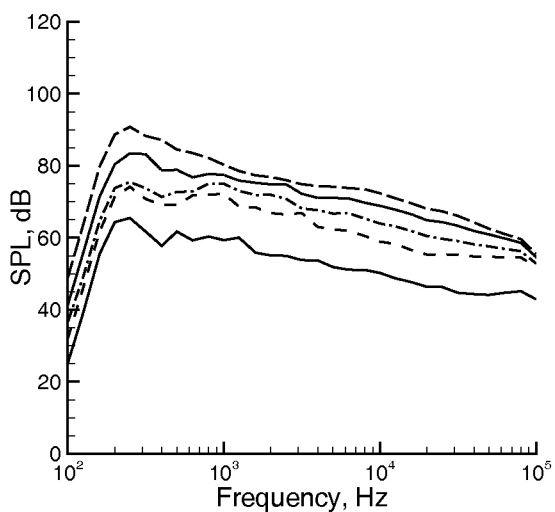
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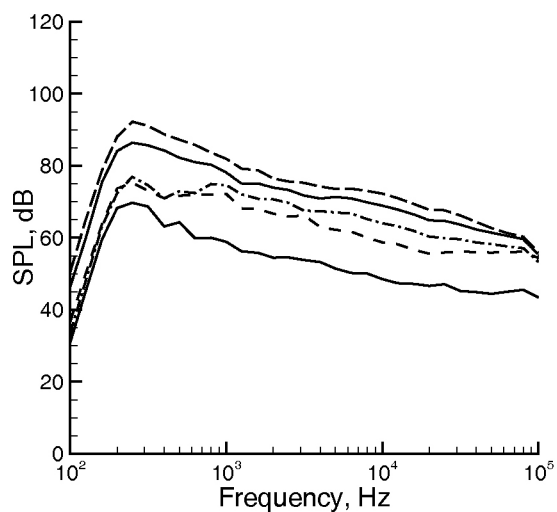
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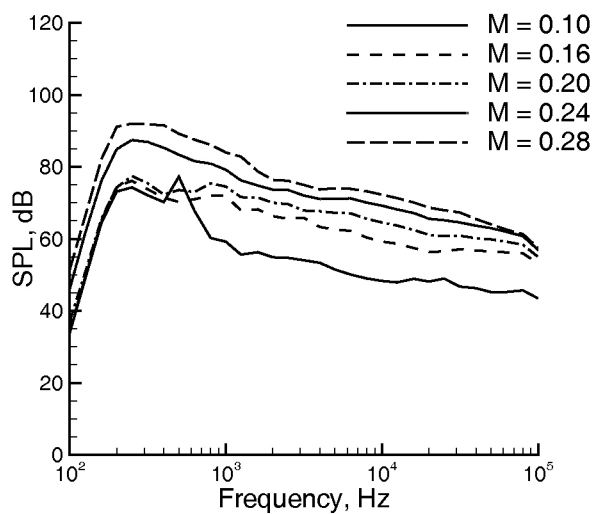


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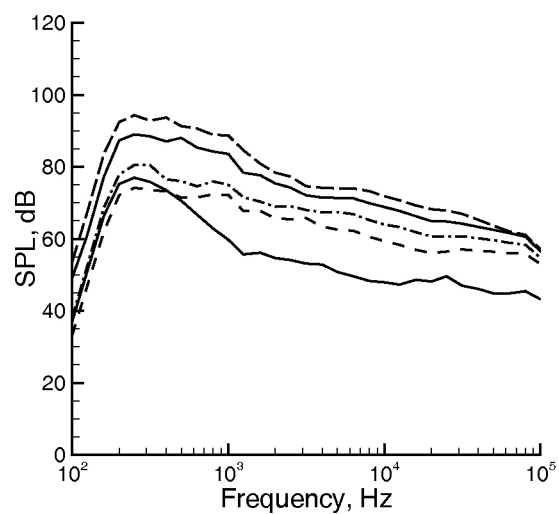


l. Microphone 12

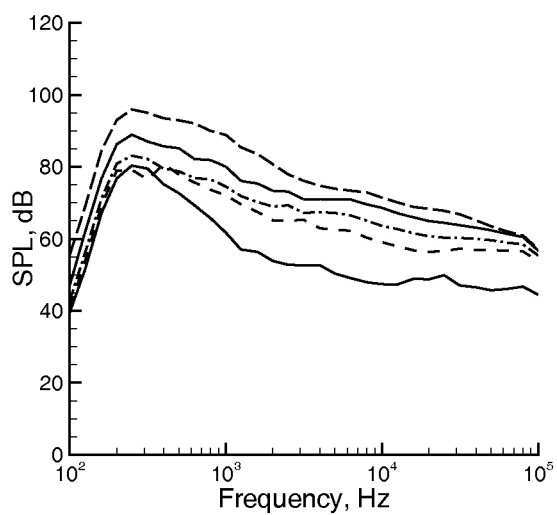
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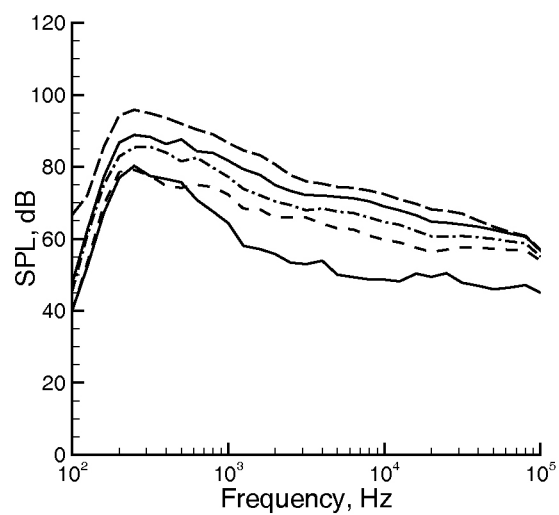
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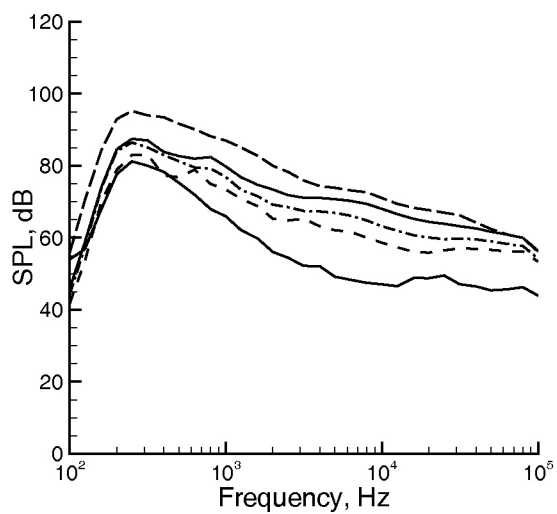
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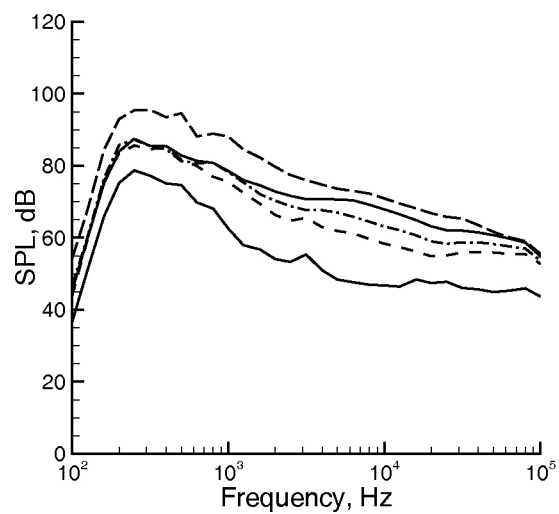
o. Microphone 15



p. Microphone 16



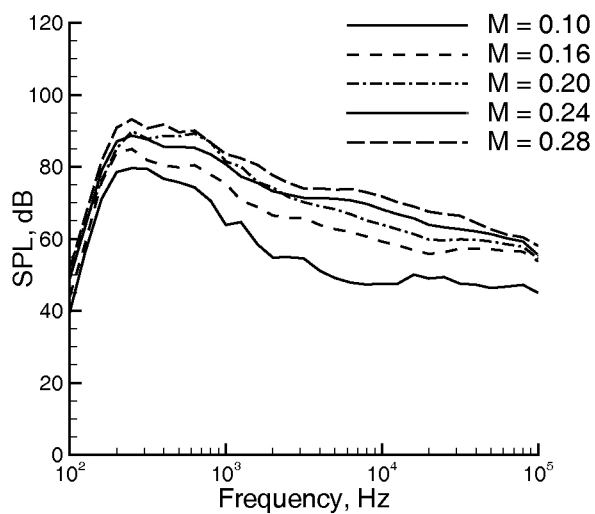
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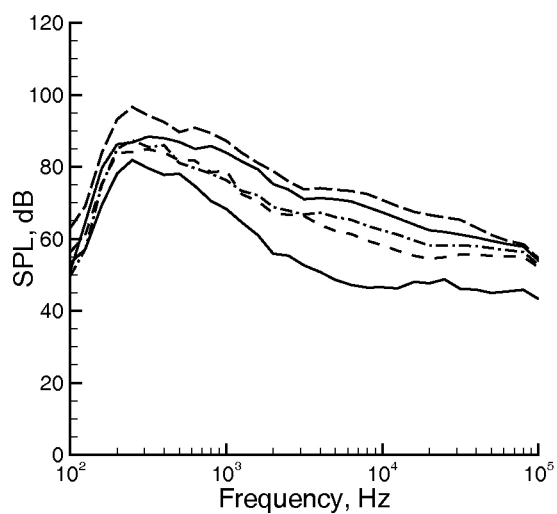
r. Microphone 18

Figure 6. Continued.

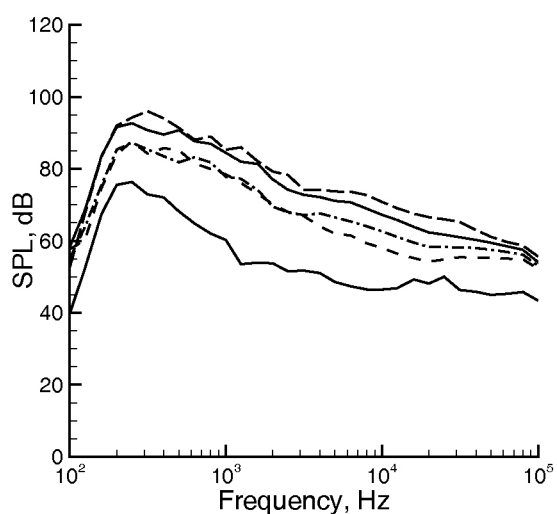




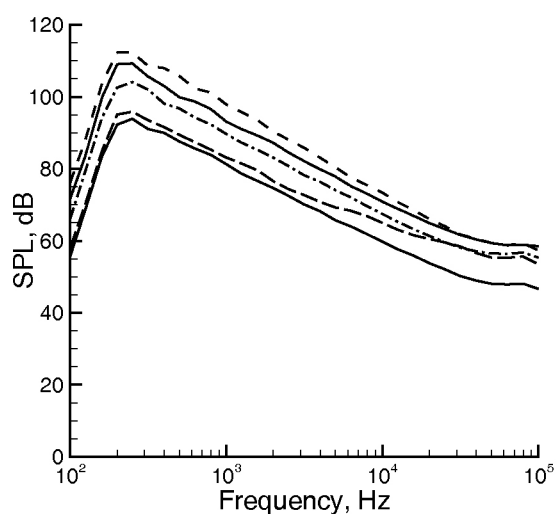
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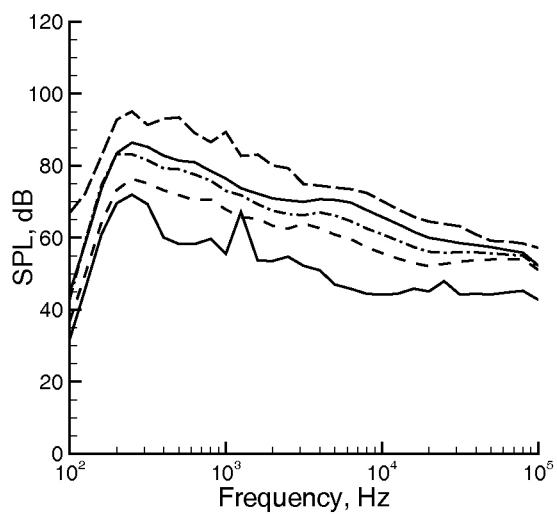
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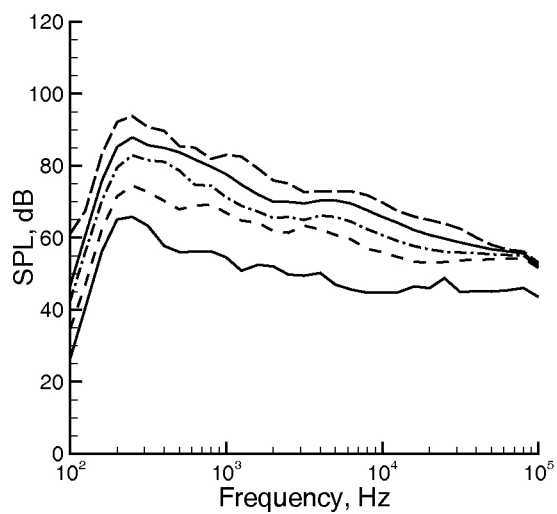
u. Microphone 21



v. Microphone 22



w. Microphone 23



x. Microphone 24

Figure 6. Continued.

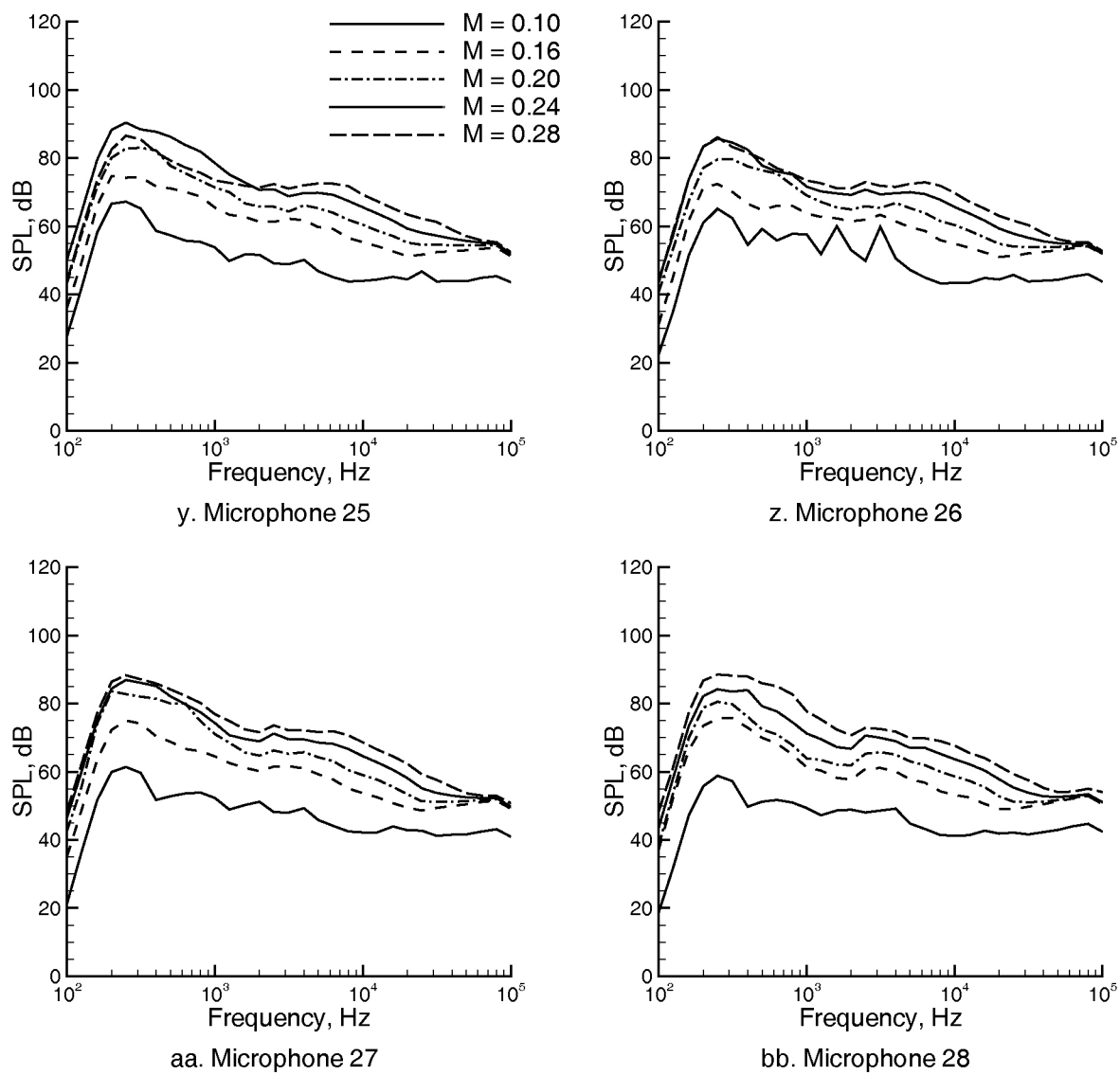
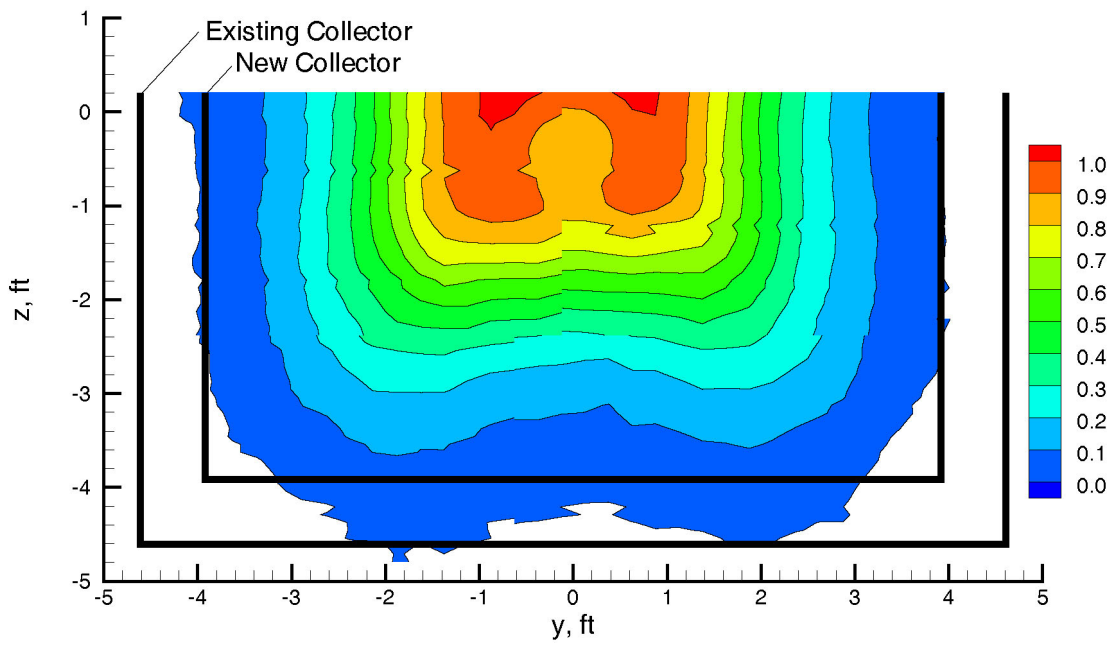
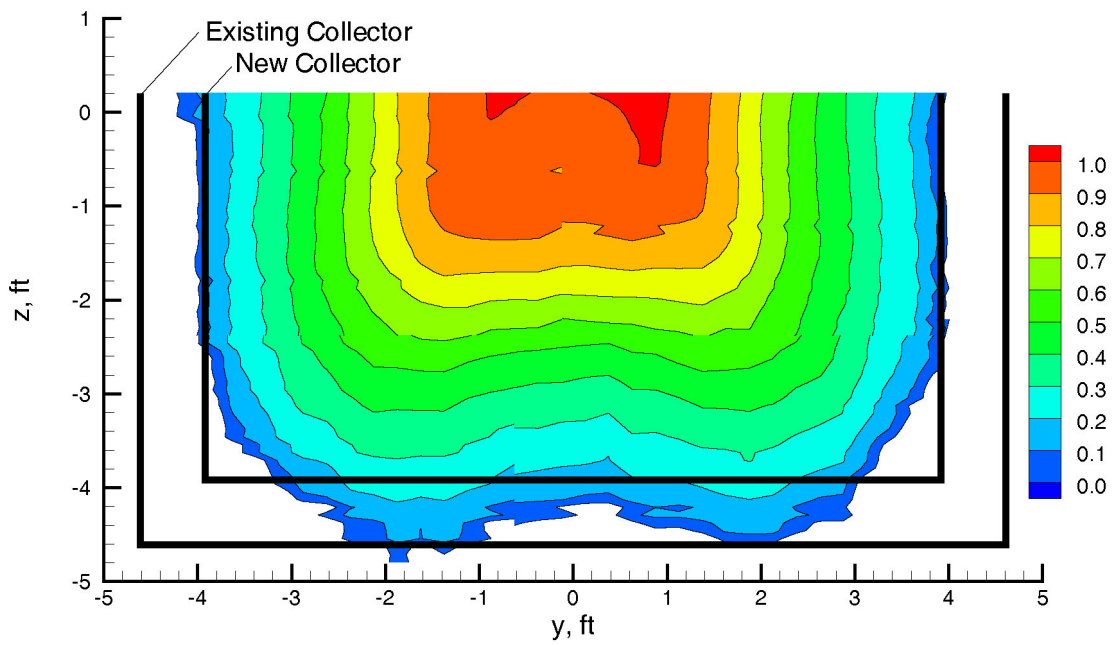


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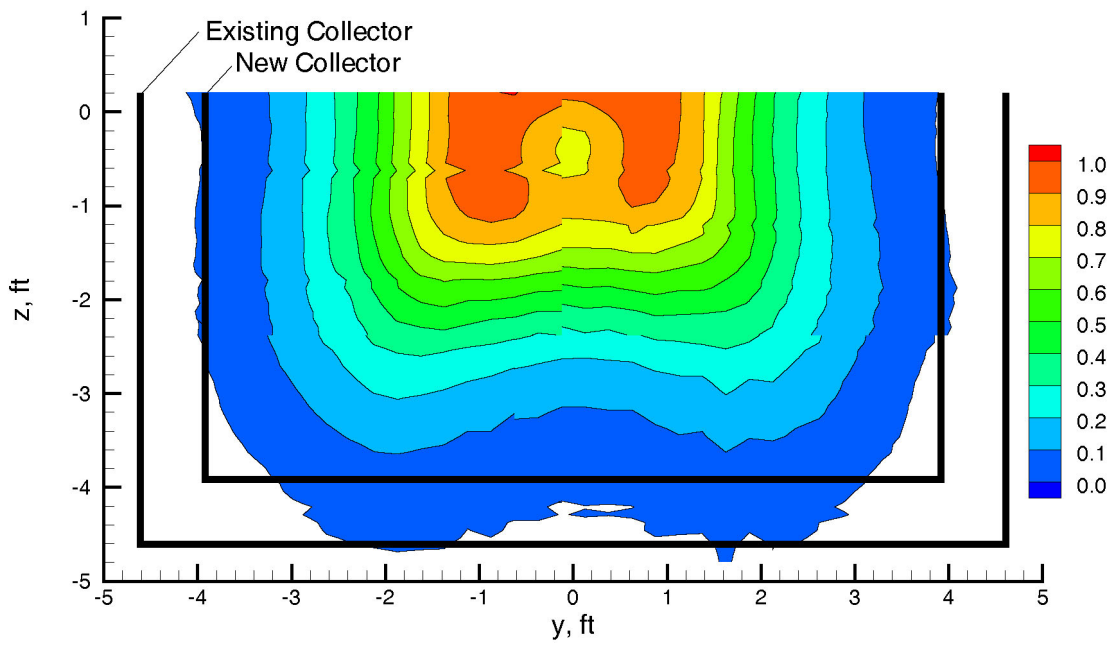


a. Normalized dynamic pressure distribution.

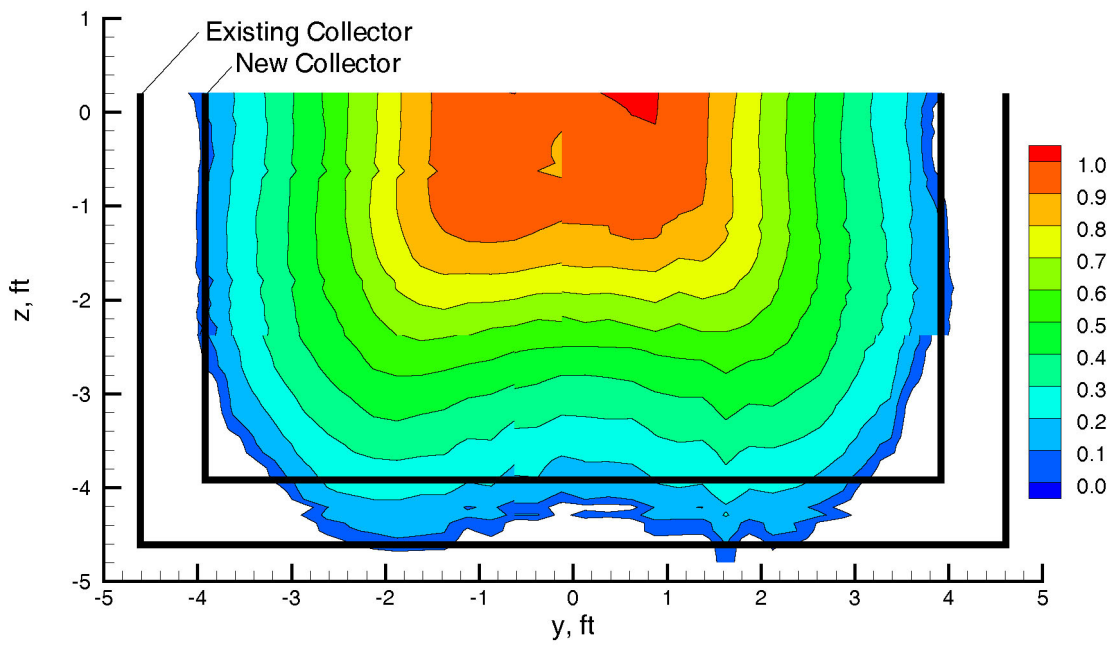


b. Normalized velocity distribution.

Figure 7- Flow survey for  $M = 0.20$ .

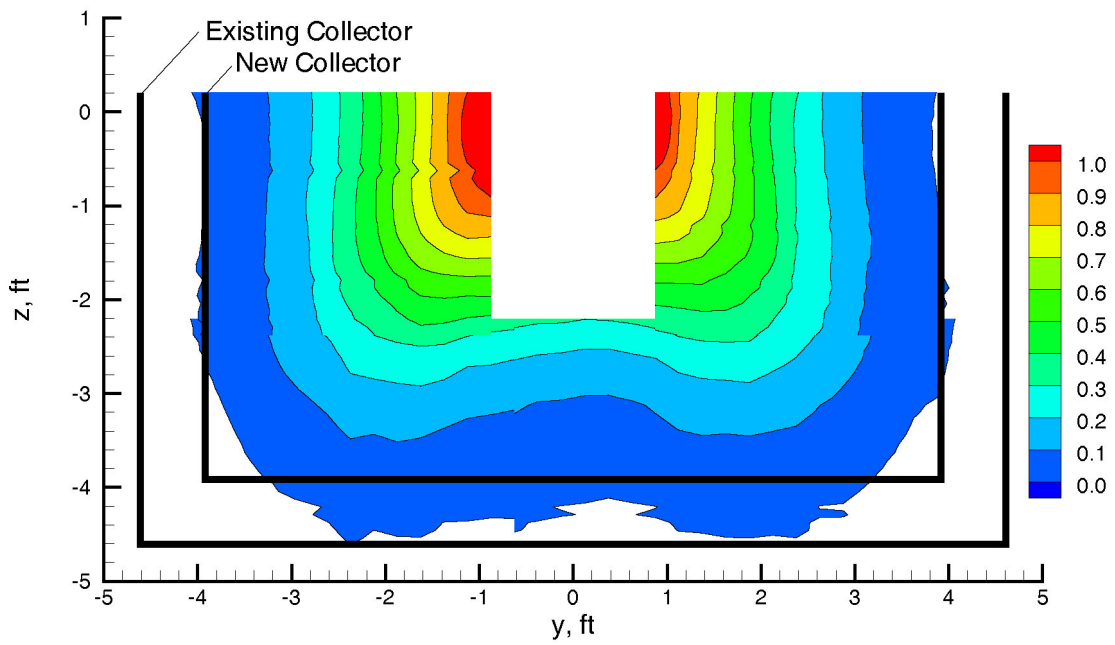


a. Normalized dynamic pressure distribution.

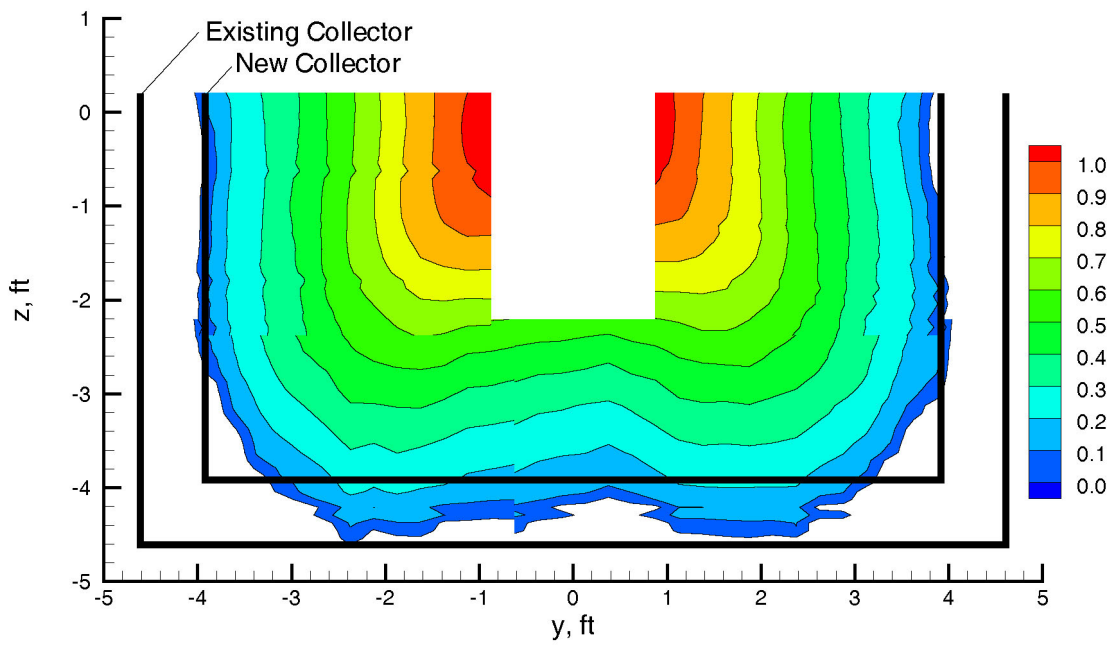


b. Normalized velocity distribution.

Figure 8 – Flow survey for  $M = 0.28$ .



a. Normalized dynamic pressure distribution.



b. Normalized velocity distribution.

Figure 9 – Flow survey for  $M = 0.28$  with JES flow on.

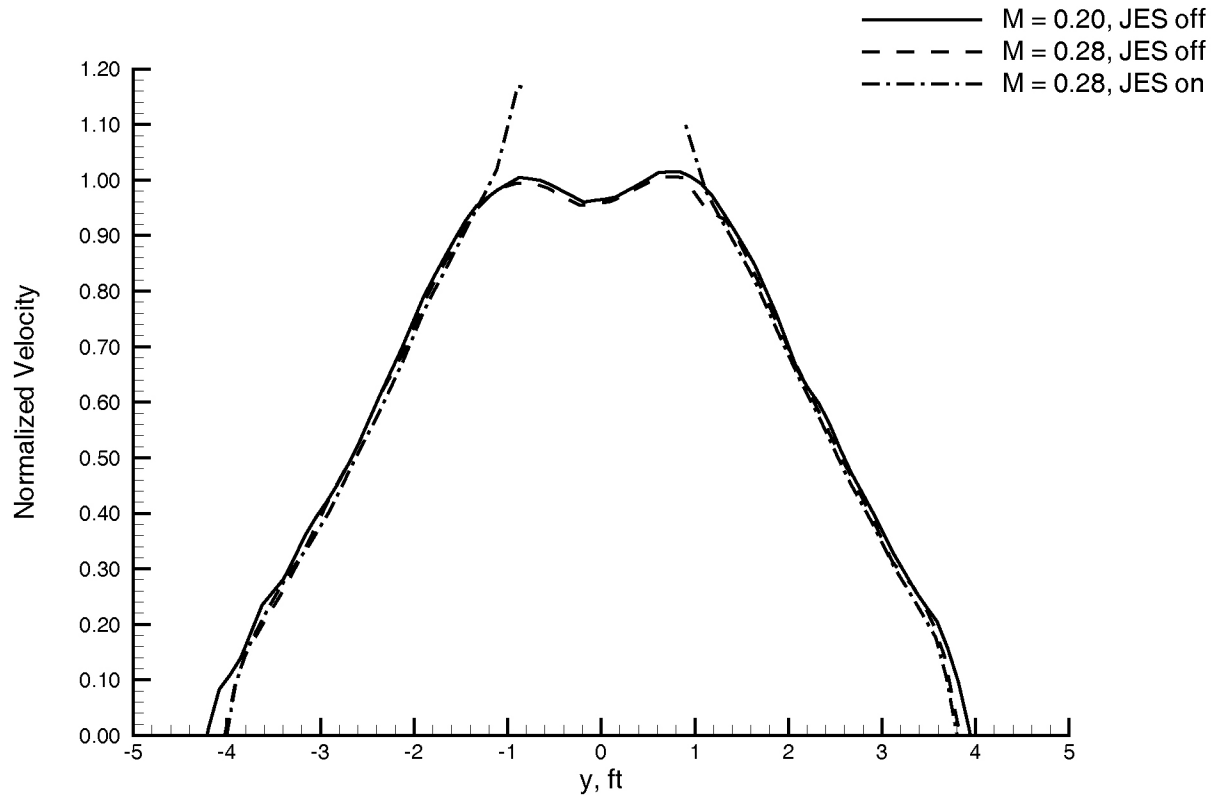


Figure 10. Comparison of normalized velocity profile at  $z = 0.05$  inches.

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14. ABSTRACT The NASA Langley Research Center Low Speed Aeroacoustic Wind Tunnel is a premier facility for model-scale testing of jet noise reduction concepts at realistic flow conditions. However, flow inside the open jet test section is less than optimum. A Construction of Facilities project, scheduled for FY 05, will replace the flow collector with a new design intended to reduce recirculation in the open jet test section. The reduction of recirculation will reduce background noise levels measured by a microphone array impinged by the recirculation flow and will improve flow characteristics in the open jet tunnel flow. In order to assess the degree to which this modification is successful, background noise levels and tunnel flow are documented, in order to establish a baseline, in this report.						
15. SUBJECT TERMS Aircraft noise reduction; Background noise; Jet noise measurement						
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